MITIGATION OF PRESCRIBED FIRE ATMOSPHERIC POLLUTION THROUGH INCREASED UTILIZATION OF HARDWOODS, PILED RESIDUES, AND LONG-NEEDLED CONIFERS

FINAL REPORT

PART I--OVERVIEW AND SUMMARY

July 15, 1989

D.V. Sandberg, D.E. Ward, R.D. Ottmar,
C.C. Hardy, T.E. Reinhardt, and J.N. Hall

IAG DE-AI179-85BP18509 (PNW-85-423)

Title: Environmental Impacts of Increased Residue/Slash Recovery

Submitted by:

USDA Forest Service
Pacific Northwest Research Station
Fire and Air Resource Management Project

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United states Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any leagal liability or product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to a specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Governemnt or any agency thereof.

The technical and statistical review of this lengthy report has been limited to detailed reviews of sections which have been published in the general literature. Future sections which will be published will also be rigorously reviewed. If errors are found in the final report, an errata sheet and revision will be published and distributed. If you would like to be on distribution list, please call or write to:

Faye Dalton
Seattle Forestry Sciences Laboratory
4043 Roosevelt Way N.E.
Seattle, WA 98105
Phone 206-442-7815

ACKNOWLEDGMENTS

This research was initiated through the support of the Pacific Northwest and Alaska Bioenergy Program, managed by Bonneville Power Administration for the U.S. Department of Energy. Several agencies, companies and individuals have cooperated in this study effort, and we would like to acknowledge our considerable debt to them. The study execution was made possible only by the cooperation provided by Region Six National Forests and Ranger Districts, Pilchuck Tree Farm (Pacific Denkmann Co.), and Champion International. Last, a special thanks to the Wallowa-Whitman, Siuslaw, and Wenatchee National Forests for additional funding support that allowed further data collection and analysis beyond the intitial study proposal.

Several people not directly affiliated with this research work unit contributed significantly to part III, Emissions Characterization. Dr. R.A. Rasmussen, Oregon Graduate Center, provided laboratory quantitation of the trace gases. The derivation of the heat flux method for calculation of fuel consumption was performed by Ms. Jennifer Long. Mr. Phillip Heft graciously developed and described new approaches to modeling of fuel consumption.

PAGE

TABLE OF CONTENTS

1.0	INTRODUCTION	1
2.0	REVIEW OF PRIOR WORK	2
3.0	GOALS	4
4.0	STUDY AREA	5
5.0	RESULTS	8
	5.1 FUEL CONSUMPTION	8
	5.2 EMISSIONS CHARACTERIZATION	9
6.0	DISCUSSION	10
	6.1 FUEL CONSUMPTION	10
	6.2 EMISSIONS CHARACTERIZATION	10
7.0	CONCLUSION	12
8.0	LITERATURE CITED	14

LIST OF FIGURES

PAGE

Figure 4.0.1 6

Fuel consumption study unit locations.

Figure 4.0.2 7

Emissions characterization study unit locations.

FINAL REPORT - PART I

OVERVIEW AND SUMMARY

Mitigation of Prescribed Fire Atmospheric Pollution Through Increased Utilization of Hardwoods, Piled Residues, and Long-needled Conifers

1.0 INTRODUCTION

The Fire and Air Resource Management Project, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle, Washington, and the U.S. Department of Energy, Bonneville Power Administration, have cooperated on a 3-year study to assess the reduction in emissions of atmospheric pollutants from prescribed burning through increased utilization of harvest residues in Oregon and Washington. The target cover types included west-coast hardwoods, mixed east-slope and short-needled conifers, and pine.

The final report is presented in three parts. This section (PART I) presents an overview and summary of the study funded by Interagency Agreement No. DE-RP79-85BP18509 (PNW-85-423). The next section (PART II) presents woody fuel and duff consumption models by combustion phase developed from ground-based inventory studies. The final section (PART III) presents results of studies that characterized smoke emissions from prescribed fires for various fuel and fire conditions. Appendices to PART III include a substantial data base from this and earlier studies that describe the chemical and physical characteristics of prescribed fire emissions.

This report concludes a series of studies conducted by the Pacific Northwest and Alaska Bioenergy Program which investigated the environmental and ecological consequences of forest residue removal. In effect, the studies promote utilization of forest biomass for energy by recognizing and demonstrating the positive results of residue removal. Forest managers now realize that residue removal substantially reduces air pollution from prescribed burning and that nutrient capital is conserved when the severity of prescribed fire is reduced. These studies give evidence of emission reduction goals on which forest managers and air-quality managers agree.

2.0 REVIEW OF PRIOR WORK

Environmental effects can be most efficiently controlled at the source. Continuing research by the Fire and Air Resource Management Project, in cooperation with the Pacific Northwest and Alaska Bioenergy Program, has answered many questions regarding environmental effects of increased residue recovery. Occasionally, residue removal eliminates the need for prescribed burning. More often, it mitigates adverse effects of broadcast burning by removing large, defective material that promotes long smoldering fires and resulting harsh effects on the site and on residual trees. Mass and duration of air pollutant emissions have been reduced, nutrient capital has been conserved, organic layer is preserved, and mineral soil remains unaltered.

Open burning of biomass produces incompletely oxidized combustion products. These materials degrade air quality primarily by contributing to the background levels of gaseous and particulate matter pollutants. In the Pacific Northwest

states, prescribed forest burning produces about 100,000 ton of particulate matter annually. Production of emissions from open fires is affected by various fuel, fire, and atmospheric variables. By performing preburn operations (i.e., residue removal or careful fire-prescription planning), the variables affecting pollution production can be used to advantage in reducing the quantity of pollutants produced.

Models and algorithms, available from earlier studies, estimate fuel consumption and emission production from broadcast burning of conifer logging slash west of the Cascade crest (Ward and Hardy 1984, Hardy and Ward 1986, Ottmar 1984, Sandberg and Peterson 1985). Full-scale demonstration projects also showed that emissions could be reduced by as much as 40 percent by increased residue removal (Sandberg 1988, Sandberg 1984, Ottmar 1987, Ottmar and others 1985). Improved chemical-source profiles of emissions strengthened the capability to distinguish smoke from slash burning through receptor modeling (Ward 1986), and a smoke-management reporting system and an emission inventory were developed to better track changes in air quality resulting from increasing utilization (Peterson 1987, Peterson and Sandberg 1988, Sandberg 1988).

A related study concluded that annual emissions have been reduced by nearly 30 percent in western Oregon and western Washington since the baseline period of 1976 to 1979, and that a substantial portion of that improvement was the result of increased utilization of harvest residues (Sandberg 1986). However, more recent work disproved the role of increased utilization in accomplishing that reduction, except on a few National forests. Although utilization is known to

reduce air-pollutant emissions on a per-unit-area basis, there is no evidence that utilization practices have improved overall (Sandberg and others 1989).

Earlier characterizations of west-side broadcast burning of Douglas-fir and western hemlock logging slash applies to about one-fourth of the land area treated by prescribed fire in Oregon and Washington. We found that removal of each ton of consumable biomass reduced duff consumption by another 1.3 tons and reduced fine particulate air-pollutant emissions by about 48 pounds. However, we were left with inadequate information for evaluating possible reduction in air pollutants through utilization of residues in other areas.

3.0 GOALS

The goal of this research is to enable scientists and managers to evaluate the possible mitigation of air pollution from prescribed fires through increased utilization of forest residues. To attain that goal, we must do the following:

3.1 Predict woody fuel and duff consumption by broadcast burning in hardwood, pine, and mixed-conifer logging slash. Objectives supporting this goal are listed in PART II.

3.2 Identify characteristics of air-pollutant emissions from the burning of hardwood, pine, and mixed-conifer broadcast logging slash and from the burning of piled logging slash. Objectives supporting this goal are listed in PART III.

4.0 STUDY AREA

This research was entirely a field study. Fuel consumption and air-pollutant emissions were measured during full-scale prescribed burning operations. The fires were prescribed by land managers to accomplish specific resource objectives and we sampled burn activity with as little alteration of the burn plan as was consistent with quality data collection. Preparation of field sites, burning operations, as well as supplemental funding was contributed by cooperating agencies and landowners.

The study area was the forested land of Oregon and Washington. Studies have been completed on the land of eight National Forests (Siskiyou, Siuslaw, Mt. Hood, Mt. Baker-Snoqualmie, Olympic, Umpqua, Deschutes, Wallowa-Whitman, Okanagon, Colville, and Wenatchee) and on the land of two private timber companies (Champion International and Pilchuck Tree Farm, Pacific Denkmann Co.). Selected units for the hardwood study ranged from southwest Oregon to northwest Washington. East-side units had a similar, wide geographical range, from central Oregon to northeast Washington (figures 4.0.1 and 4.0.2). Units were selected strictly on the basis of operability, likelihood to be burned on schedule, contribution to wide geographical representation, and on the willingness of a land manager to cooperate in the research effort.

Twenty hardwood clearcut units were selected and burned (selection of 9 to 12 was originally proposed) to develop predictive algorithms for biomass consumption (see PART II). Concurrent emission sampling was completed on eight of the hardwood units (see PART III).

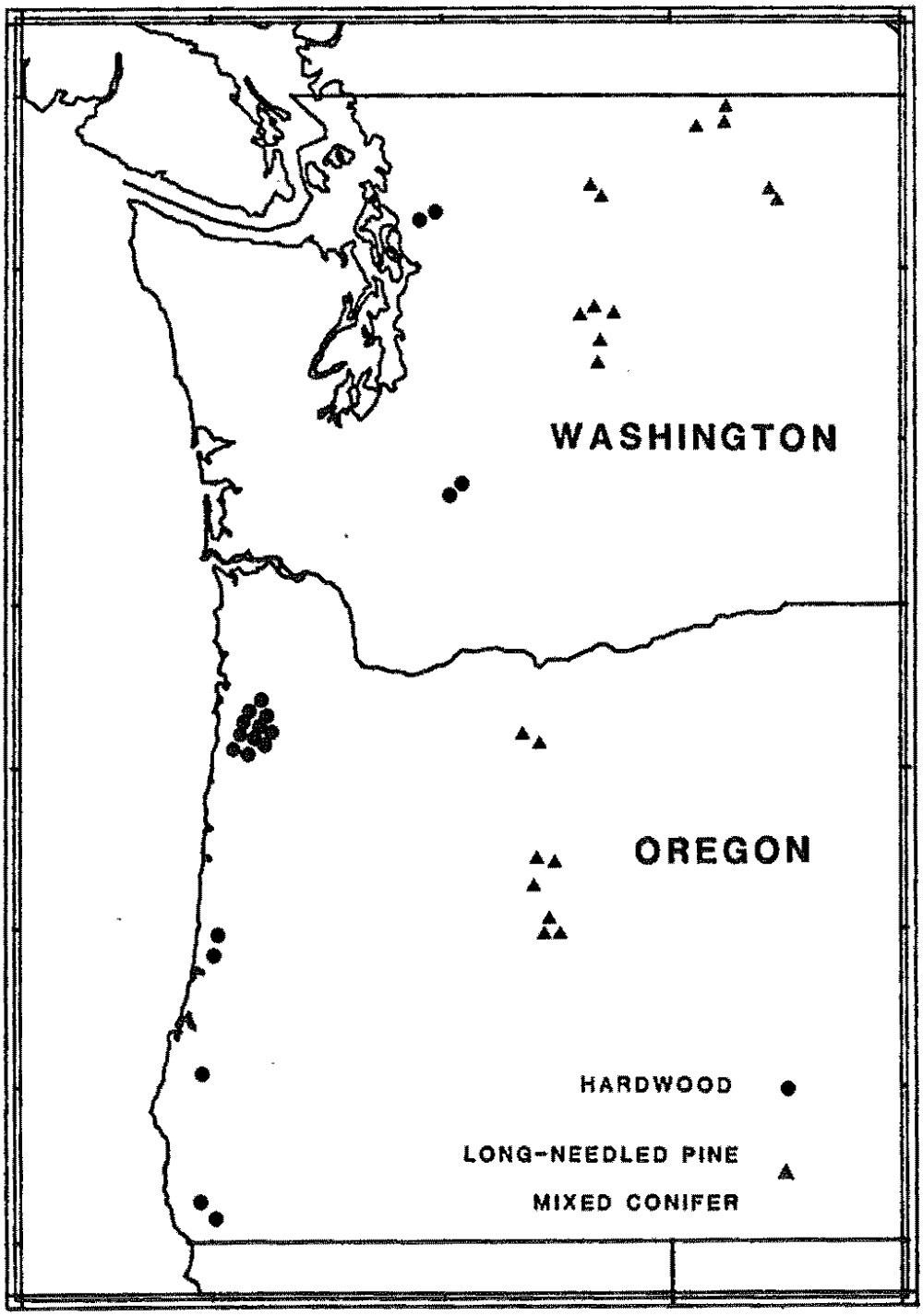


Figure 4.0.1. Fuel consumption study unit locations.

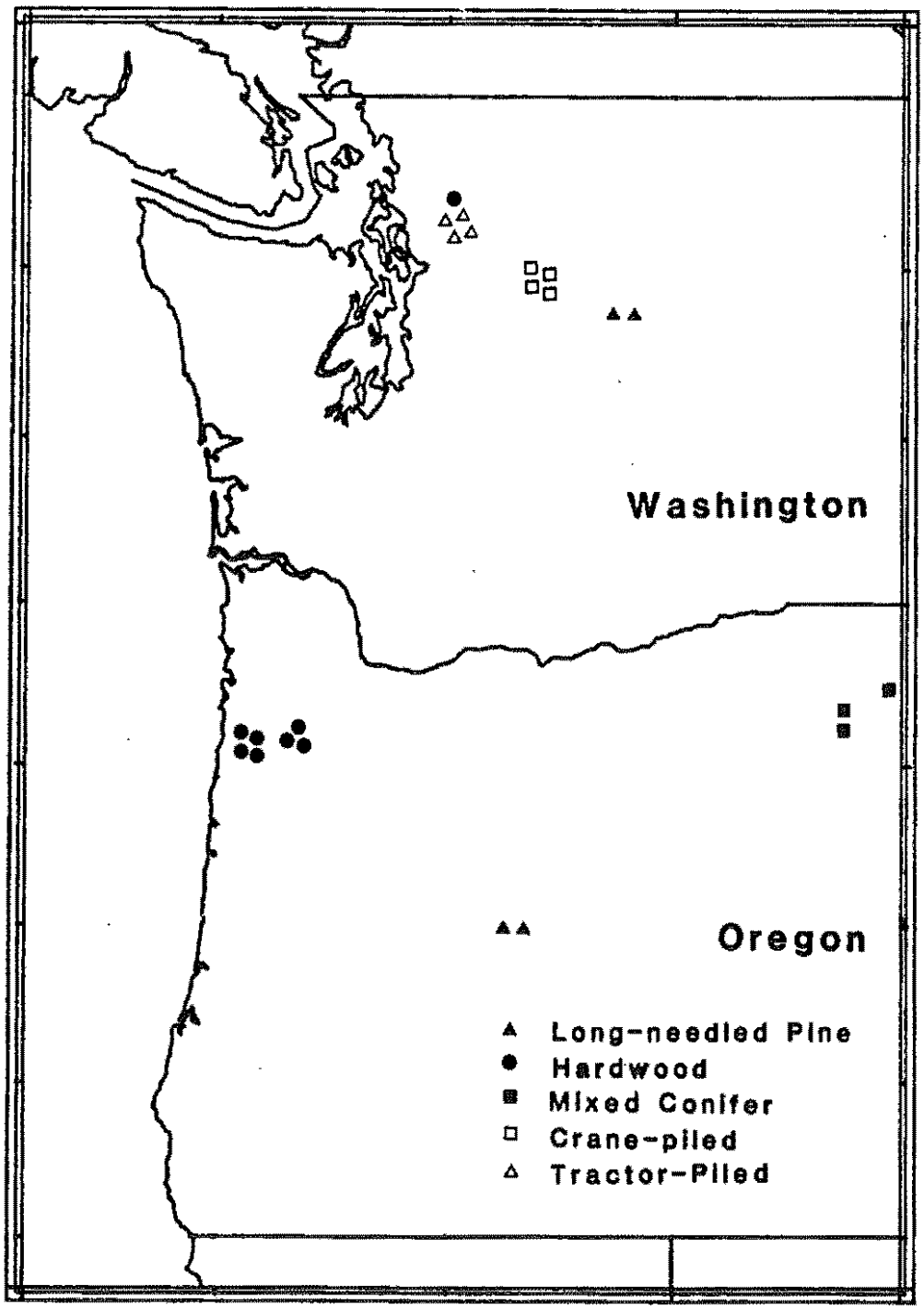


Figure 4.0.2. Emissions characterization study unit locations.

Twenty units (selection of 9 to 12 was originally proposed) in harvested east-side mixed conifer and pine areas were burned for the biomass consumption study. Seven of the east-side mixed conifer and pine units were also sampled for emissions. In addition, four short-needled conifer piles on the Mt. Baker-Snoqualmie National Forest and four piles on the Pilchuck Tree Farm were sampled for emissions.

Detailed methods for each objective are described in PARTS II and III.

5.0 RESULTS

5.1 FUEL CONSUMPTION

Results indicate that the relationship between fuel moisture and large, woody fuel consumption in both west-side hardwood and east-side, short-needled and pine logging slash is similar to results obtained from west-side Douglas-fir and western hemlock slash burns (Sandberg and Ottmar 1983). The relationship between duff consumption and large fuel consumption for hardwoods is also similar to results found for Douglas-fir and western hemlock burns (Ottmar and others 1985). Consumption of duff in pine units is similar to predictive equations developed for shallow-duff sites in western Oregon and Washington, although less duff consumption occurred per ton of fuel consumed because the duff-bulk density on pine sites is less than that measured on the westside.

Consumption of fuels that are 1 to 3 inches in diameter was shown to be the controlling variable for both hardwood and east-side species in predicting the

proportion of large fuel consumption which occurs during the flaming phase. The flaming phase of duff consumption was shown to be controlled by diameter reduction of large fuels during flaming phase. Further data collection and analysis will be needed, however, to finalize this conclusion.

5.2 EMISSIONS CHARACTERIZATION

Emissions from prescribed burning were characterized on twenty-three operational-scale tests in Oregon and Washington. The test areas were selected to represent fuel and fire types not previously studied, which included broadcast burning of clearcuts in three different fuel types (hardwoods, long-needled pine, and mixed conifer) and pile burns of crane-piled slash and tractor-piled slash.

The observed and calculated variables from the 23 emissions characterization tests were compared with data from previous research in the Douglas-fir/hemlock (short-needled conifer) fuel type. Significant differences in emissions between the piled tests and the broadcast burns were expected and observed. Heat release rates for the piled tests were a factor 2-3 greater than for the broadcast burns. Emission factors for the broadcast burns were more similar between fuel types than expected. Emission factors for CO were similar for mixed conifer, long-needled pine, and hardwoods. The only difference in fine particulate emission factors was between long-needled pine and hardwood--the two least similar fuel types. Large variances in some of the variables diminished the strength of many of the correlations present.

6.0 DISCUSSION

6.1 FUEL CONSUMPTION

The independant variables which best correlated with fuel consumption of hardwood and east-side fuel types were the same as the variables found to control the fuel consumption for Douglas-fir and western hemlock. Fuel moisture controlled the woody fuel consumption while total heat load and duration of heat controlled duff consumption. Although in some cases the relationship between the variables and the type of consumption were weak, they were the best relationships found from the analysis. The weak relationships are probably due to the considerable variation we had in burning conditions between units and the limited number of data points.

In most cases, analysis of covariate techniques indicated there were no significant difference between the hardwood and east-side algorithms compared with algorithms developed for westside Douglas-fir and western hemlock prescribed fires.

6.2 EMISSIONS CHARACTERIZATION

No other emissions characterization research has resulted in a body of information more extensive or reliable than that contained in this report. The information presented in Part III forms the basic data set from which a diversity of continuing research and reporting will be performed.

The emissions characterization research has been directed toward describing differences in emissions between various fuel and fire types as well as between treatment options within a given fuel type. Although significant differences between the piled-slash tests and broadcast burns were observed for most variables, the differences in emissions between fuel and fire types has not been as significant as expected (when evaluated at the 95 percent level of confidence).

Any interpretation of these data must include a clear understanding of their application. A dichotomy may well exist in the interpretation of "the significance" of certain differences. For example, where the statistical treatment of the data presented in this report may have determined that no difference in the PM emission factor exists between hardwoods and mixed conifers, the absolute difference of over 4 lb/ton could have a very large impact on an annual inventory of emissions. It is reasonable to assume that where scientific applications of the data may have rejected the difference, applications of the data to air quality or smoke management decisions may appropriately use 50 percent confidence intervals (or lower).

The concept of a parametric emissions production model requires the description and proof of strong relationships between independent variables easily observed or predicted and key independent variables. While the correlations presented in this report do not necessarily imply causation, progress has been made in the understanding of certain associations. It is also apparent, however, that earlier expectations of the use of reaction intensity as a predictive variable for the source strength of certain primary emissions may not be achieved. It

is not clear how the conflict of scaling versus control of parameters can be resolved between field-scale tests and laboratory experiments.

7.0 CONCLUSIONS

As a result of the fuel consumption (part II) and emission characterization study (part III), we can quantitatively evaluate the opportunity to mitigate emissions produced from prescribed fire for hardwood, pine, and mixed conifer broadcast burn units. In addition, this study has provided an ability to evaluate emissions mitigation through inferences and quantitative estimates for slash piles and ponderosa pine prescribed fires. Other conclusions from the studies include:

1. Increased utilization of residues is an effective means of reducing air pollutants from prescribed fire. That has been known for several years, but the technique has not been widely used in the Pacific Northwest probably because of the lack of quantitative predictive evaluation tools.

2. Forest managers and air quality managers will now be provided with quantitative tools to plan effective utilization programs to reduce air pollution emissions.

3. Emission factors for criteria pollutants for hardwoods, pine, mixed conifer, and piled-slash fuel types are now available for use. The emission factors represent each phase of combustion as well as the total (weighted average) fire.

4. The difference between emission factors for these species and for short-needled conifer is small compared to the variability within fuel types. Consequently, development of a parametric model to predict emissions should concentrate on fire behavior and fuelbed conditions rather than species.

5. Measurements of certain trace gases have provided data for further analysis of their source characteristics relative to other variables discussed in this report.

6. Profiles of trace elements and organic and graphitic carbon have been developed for all of the fuel and fire situations discussed in this report. The profiles are being used to determine the relative effects of the apportionment of prescribed burning sources affecting regional levels of ambient air quality.

8.0 LITERATURE CITED

Hardy, Colin C.; Ward, Darold E. 1986. Emission factors for particulate matter by phase of combustion from prescribed burning. In: Proceedings of the 1986 Annual Meeting of the Pacific Northwest International Section, Air Pollution Control Association; 1986 November 19-21; Eugene, OR.

Ottmar, Roger D. 1984. Predicting fuel consumption by fire stages to reduce smoke from slash fires. In: Proceedings, annual meeting of the Northwest Fire Council; 1983 November 21-22; Olympia, WA. Portland, OR: Northwest Fire Council: 87-106.

Ottmar, Roger D. 1987. Reducing smoke from prescribed fires; research solution to a management problem. In: Proceedings, Annual Meeting of the Northwest Fire Council; 1986 November 18-19; Olympia, WA. Portland, OR: Northwest Fire Council. 16 p.

Ottmar, Roger D.; Little, Susan N.; Ohmann, Janet L. 1985. Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. In: Proceedings, 8th Conference on Fire and Forest Meteorology; 1985 April 29 - May 2; Detroit, MI. Bethesda, MD: Society of American Foresters: 139-144.

Peterson, Janice L. 1987. Analysis and reduction of the errors of predicting prescribed burn emissions. Seattle, WA: University of Washington, College of Forest Resources. 70 p. (Thesis).

Peterson, J.L.; Sandberg, D.V. 1988. A national PM10 emissions inventory approach for wildfires and prescribed burning. In: Mathai, C.V.; Stonefield, David H., eds. Transactions, PM-10 Implementation of Standards: An APCA/EPA International Specialty Conference; 1988 February 23-24; San Francisco, CA. Pittsburgh, PA: Air Pollution Control Association.

Sandberg, David V. 1984. Give the forest industry credit for reducing smoke emissions. In: Seminar on wood-derived fuels: Proceedings of the U.S. Department of Energy and the Pacific Northwest Bioenergy Group; 1984 May 10-11; Portland, OR. Washington, DC: Department of Energy. [Not paged].

Sandberg, D.V. 1986. Progress in reducing emissions from prescribed forest burning in western Washington and western Oregon. In: Proceedings of the 1986 annual meeting of the Pacific Northwest International Section, Air Pollution Control Association; 1986 November 19-21; Eugene, OR. Pittsburg, PA: Air Pollution Control Association: 24-33.

Sandberg, David. 1988. Improved air-resource management by reducing smoke from prescribed fires. In: Woodfin, R.O., Jr., ed. Forest Residues. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. [Not paged].

Sandberg, David. 1988. Techniques for reducing smoke from prescribed fire. In: Woodfin, R.O., Jr., ed. Forest Residues. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. [not paged].

Sandberg, David V.; Peterson, Janice L. 1985. A source strength model for prescribed fires in coniferous logging slash. In: Proceedings of the Pacific Northwest International Section of the Air Pollution Control Association Annual Meeting; 1984 November 12-14; Portland, OR. Portland, OR: Air Pollution Control Association: 10 p.

Sandberg, D.V.; Peterson, J.L.; Ottmar, R.D.; Barnes, D.A.; Mikowski, J.L. [In press]. Effect of utilization practice trends on air pollution from slash burning. U.S. Department of Energy, Pacific Northwest and Alaska Regional Biomass Energy Program, Bonneville Power Administration; final report; IAG DE-A179-86BP60175 (PNW-86-472).

Ward, Darold E. 1986. Characteristic emissions of smoke from prescribed fires for source apportionment. In: Proceedings of the 1986 Annual Meeting of the Pacific Northwest International Section, Air Pollution Control Association; 1986 November 19-21; Eugene, OR. Pittsburg, PA: Air Pollution Control Association: 160-167.

Ward, Darold E.; Hardy, Colin C. 1984. Advances in the characterization and control of emissions from prescribed fires. Paper No. 84-36.3. Presented at the 78th annual meeting of the Air Pollution Control Association; 1984 June 24-29; San Francisco, CA. Pittsburg, PA: Air Pollution Control Association. 32 p.

4. The difference between emission factors for these species and for short-needled conifer is small compared to the variability within fuel types. Consequently, development of a parametric model to predict emissions should concentrate on fire behavior and fuelbed conditions rather than species.

5. Measurements of certain trace gases has provided data for further analysis of their source characteristics relative to other variables discussed in this report.

6. Profiles of trace elements and organic and graphitic carbon have been developed for all of the fuel and fire situations discussed in this report. The profiles are being used to determine the relative effects of the apportionment of prescribed burning sources affecting regional levels of ambient air quality.

MITIGATION OF PRESCRIBED FIRE ATMOSPHERIC POLLUTION THROUGH INCREASED UTILIZATION OF HARDWOODS, PILED RESIDUES, AND LONG-NEEDLED CONIFERS

FINAL REPORT

PART II--FUEL CONSUMPTION

July 15, 1989

R.D. Ottmar, D.V. Sandberg, and J.N. Hall

IAG DE-AI179-85BP18509 (PNW-85-423)
Title: Environmental Impacts of Increased Residue/Slash Recovery

Submitted by:

USDA Forest Service
Pacific Northwest Research Station
Fire and Air Resource Management Project

FINAL REPORT - PART II

FUEL CONSUMPTION

Mitigation of Prescribed Fire Atmospheric Pollution Through Increased Utilization of Hardwoods, Piled Residues, and Long-needled Conifers

ABSTRACT

Woody fuel and duff consumption were measured on 40 operational, prescribed burns on National Forest and private lands in Oregon and Washington during 1985 and 1986. Twenty of the units were dominated by west-coast red alder, vine maple, and tanoak residues. The remaining 20 units were dominated by slash from east-side mixed confier or long-needled-pine slash.

Models to predict consumption of large woody fuels and duff were developed from data collected. The amount of large, woody material consumed during the fire is controlled by internal fuel moisture. Consumption of small fuels controls how much large woody material is consumed during the flaming combustion phase.

Duff consumption is predicted by the moisture content of duff and by heat generated from the consumption of woody fuels. Flaming duff consumption depends on the consumption of large, woody fuels which occurs during the flaming phase.

Fuel consumption equations developed from this study were compared with fuel consumption equations previously formulated for prescribed burns of west-coast Douglas-fir and western hemlock. In most cases, no significant differences were found between the equations.

PAGE

TABLE OF CONTENTS

1.0	INTRODUCTION	1
2.0	REVIEW	2
3.0	OBJECTIVES	10
4.0	METHODS	11
5.0	RESULTS	13
	5.1 PREBURN FUEL-HARDWOOD UNITS	13
	5.2 PREBURN FUEL-EAST-SIDE UNITS	18
	5.3 FUEL MOISTURE HARDWOOD UNITS	18
	5.4 FUEL MOISTURE-EAST-SIDE UNITS	19
	5.5 FUEL CONSUMPTION-HARDWOOD UNITS	19
	5.6 FUEL CONSUMPTION-EAST-SIDE UNITS	20
6.0	DISCUSSION	20
	6.1 FUEL CONSUMPTION MODELS-HARDWOODS	20
	6.1.1 LARGE, WOODY FUEL CONSUMPTION	20
	6.1.2 DUFF CONSUMPTION	26
	6.2 FUEL CONSUMPTION MODELS-EAST-SIDE	31
	6.2.1 LARGE, WOODY FUEL CONSUMPTION	31
	6.2.2 DUFF CONSUMPTION	36
	6.3 COMPUTER MODEL CONSUME	38
7.0	CONCLUSION	40
8.0	APPLICATION OF RESULTS	43
9.0	REFERENCES	45
10.	GLOSSARY	49
11.0	METRIC EQUIVALENTS	50
12.0	SCIENTIFIC AND COMMON NAMES OF TREE SPECIES	50

LIST OF TABLES

PAGE

Table 1 7

Fuel consumption regression equations developed for western Oregon and western Washington prescribed fires in the Douglas-fir and western hemlock cover type. The equations include 1) unit-average diameter reduction (DRED, inches) based on fuel moisture content (MEAS, percent); 2) flaming stage proportion (FPROP) based on 1- to 3-inch diameter woody fuel consumption (SMCON, tons/acre); 3) unit average duff reduction (DUFRED, inches) based on large fuel consumption (LGCON, tons/acre) and large-fuel diameter reduction (DRED, inches); and 4) flaming duff reduction (FDUFRED, inches) based on flaming diameter reduction of the large fuels (FDRED, inches).

Table 2 9

Current knowledge of fuel consumption by cover and burn type and fuelbed component for activity fuels. The highlighted numbers show an increase in knowledge level because of this interagency agreement. The level of burning activity for each cover-type component has been estimated.

Table 3 14

Unit and fuel data summary for westside hardwood units.

Table 4 15

Fuel consumption summary for westside hardwood units.

Table 5 16

Unit and fuel data summary for east-side units.

Table 6 17

Fuel consumption summary for east-side units.

Table 7 21

Regression equations for unit-average diameter reduction (DRED, inches) based on measured large-fuel moisture content (MEAS, percent) for hardwood (HD) and Douglas-fir/western hemlock (DF/H) units. All regression equations are at the 95-percent confidence level.

PAGE

Table 8 24

Regression equations for flaming proportion (FPROP) based on 1- to 3-inch woody fuel consumed (SMALLCON, tons/acre) for hardwood (HD) and Douglas-fir/western hemlock (DF/H) units. All regressions are at the 95-percent level.

Table 9 26

Regression equations for unit-average duff reduction (DUFRED, inches) based on large-fuel consumption (LGCON, tons/acre) and large-fuel diameter reduction (DRED, inches) for hardwood (HD) and Douglas-fir/western hemlock units. All regressions are at the 95-percent level.

Table 10 29

Regression equations for flaming duff reduction (FDUFRED) based on flaming diameter reduction of the large, woody fuels (FDRED) for hardwood (HD) and Douglas-fir/hemlock (DF/H) units. The best fit was flaming duff reduction on preburn duff depth (DUFDEP). All regressions are at the 95-percent level.

Table 11 31

Regression equation for unit-average diameter reduction (DRED,inches) based on large-fuel moisture content (MEAS, percent) for east-side long-needled pine and mixed conifer (LNP/MC) units and Douglas-fir/western hemlock (DF/H) units. All regressions are at the 95-percent level.

Table 12 33

Regression equation for flaming proportion (FPROP) based on 1- to 3-inch woody fuel consumed (SMALLCON, tons/acre) for east-side long-needled pine and mixed conifer (LNP/MC) units and Douglas-fir/western hemlock (DF/H) units. All regressions are at the 95-percent level.

Table 13 36

Regression equations for unit-average duff reduction (DUFRED, inches) based on large-fuel consumption (LGCON, tons/acre) and large-fuel diameter reduction for east-side long-needled pine and mixed conifer (LNP/MC), and Douglas-fir/western hemlock (DF/H) units. All regressions are at the 95-percent level.

PAGE

Table 14 38

Regression equations for flaming duff reduction (FDUFRED) based on flaming diameter reduction of the large, woody, fuels (FDRED) for long-needled pine and mixed conifer (LNP/MC) and Douglas-fir/hemlock (DF/H) units. All regressions are at the 95-percent level.

Table 15 41

Current knowledge of fuel consumption by cover and burn type and fuel bed component for activity fuels. The highlighted numbers show the increase in knowledge level because of this interagency agreement. The level of burning activity for each cover type component have been estimated.

LIST OF FIGURES

PAGE

Figure 1 3

Regression of unit-average large fuel diameter reduction on measured fuel moisture. Data was collected from Douglas-fir/ western hemlock prescribed burns located in western Oregon and western Washington. Confidence bands are at the 95 percentile and are for the regression line.

Figure 2 4

Regression of flaming proportion of large fuel consumption on consumption of 1- to 3-inch diameter woody fuels. Data was collected from Douglas-fir and western hemlock prescribed burns located in western Oregon and western Washington.

Figure 3 5

Regression of unit-average duff reduction on large fuel consumption for units burned with less than 25 days since significant rain and greater than or equal to 25 days since significant rain. Data was collected from Douglas-fir and western hemlock burns located in western Oregon and western Washington. Confidence bands are at the 95 percentile and are for the regression line.

Figure 4 6

Regression of flaming duff reduction on flaming diameter reduction of the large fuels. Data was collected from Douglas-fir and western hemlock prescribed burns located in western Oregon and western Washington. Confidence bands are at the 95 percentile and are for the regression line.

Figure 5 23

Large fuel diameter reduction plotted against measured fuel moisture for hardwood slash burns. The solid regression line represents the fuel moisture and fuel diameter reduction relationship established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression line.

PAGE

Figure 6 25

Flaming proportion of large fuel consumption plotted against consumption of 1- to 3-inch diameter woody fuels for hardwood prescribed burns. Regression lines are displayed for hardwood and Douglas-fir and western hemlock units.

Figure 7 27

Duff reduction plotted against large fuel consumption for hardwood units burned with less than 25 days since significant rain and greater than or equal to 25 days since significant rain. The solid regression line represents large fuel consumption and duff reduction relationship established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression lines.

Figure 8 30

Flaming duff reduction plotted against large fuel flaming diameter reduction for hardwood units. The solid regression line represents large fuel flaming diameter reduction and duff reduction relationship established for Douglas-fir/ western hemlock prescribed fires. Confidence bands are at the 95 percentile and are for the regression line.

Figure 9 33

Large fuel diameter reduction plotted against measured fuel moisture for long-needled pine and mixed conifer burns on the east-side. The solid regression line represents the fuel moisture and fuel diameter reduction established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression line.

Figure 10 35

Flaming proportion of large fuel consumption plotted against consumption of 1- to 3-inch diameter woody fuels for long-needled pine and mixed conifer prescribed burns on the east-side. Regression lines are displayed for the east-side and Douglas-fir and western hemlock units.

PAGE

Figure 11 37

Duff reduction plotted against large fuel consumption for long-needled pine and mixed conifer unites burned with less than 25 days since significant rain and greater than or equal to 25 days since significant rain. The solid regression represents large fuel consumption and duff reduction relationship established for Douglas-fir and western hemlock prescribed burns. Regression lines Confidence bands are at the 95 percentile and are for the regression line.

Figure 12 39

Flaming duff reduction plotted against large fuel flaming diameter reduction for long-needled pine and mixed conifer prescribed burns on the eastside. Regression lines are displayed for east-side units and for Douglas-fir and western hemlock units.

1.0 INTRODUCTION

The Fire and Air Resource Management Project, U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Seattle, Washington, and the U.S. Department of Energy, Bonneville Power Administration, completed a cooperative 3-year study to assess the reduction in emissions of atmospheric pollutants from prescribed burning through increased utilization of harvest residues in Oregon and Washington. The target cover types included west-coast hardwoods, east-slope mixed short-needled conifers, and pine.

The final report is presented in three parts. This section (PART II) summarizes the fuel consumption accomplishments of Interagency Agreement No. DE-AI179-85BP18509 (PNW-85-423). The potential for mitigating air pollution from prescribed fire through increased utilization of hardwood logging slash, piled residues, and harvest residues from long-needled and mixed conifer stands in eastern Oregon and eastern Washington can now be better assessed with improved fuel consumption models.

2.0 REVIEW

Fuel consumption is one of the most critical variables controlling production of smoke emissions from prescribed fires. In fact, errors in estimation of fuel consumed can result in greater uncertainties than would occur with the lack of accurate emission factors (Sandberg and Peterson 1985). Emission factors vary in different combustion phases, which requires a separation by

fire phase of fuel consumed. Using a single emission factor can impart an additional 65-percent error in estimation of total emissions from a prescribed fire (Sandberg and Peterson 1984).

Research has been conducted on fire behavior prediction for many of the various fuels found in western states. Several references contain information on changes in fuel loading that result from prescribed burning. However, there is little available information on modeling fuel consumption for prescribed burning from preburn input variables in different activity fuels.

Fuel consumption research undertaken in 1980 has provided reasonable equations for predicting consumption in Douglas-fir and western hemlock fuels by combustion phase in western Washington and Oregon (Sandberg and Ottmar 1983, Ottmar and others 1985, Ottmar 1986). Nearly 100 research units were established to monitor fuel consumption. Data analysis indicated that consumption of large woody fuels is controlled by internal fuel moisture which can be predicted from weather variables (figure 1). Flaming stage combustion of large fuels is controlled by small-fuel consumption (figure 2). Duff consumption is controlled by preburn duff-depth, large fuel consumption, and days since significant rainfall of greater than or equal to 0.50 inch (figure 3). Flaming stage consumption of duff is controlled by the flaming consumption of large woody fuels (figure 4). All regression equations have been presented in table 1.

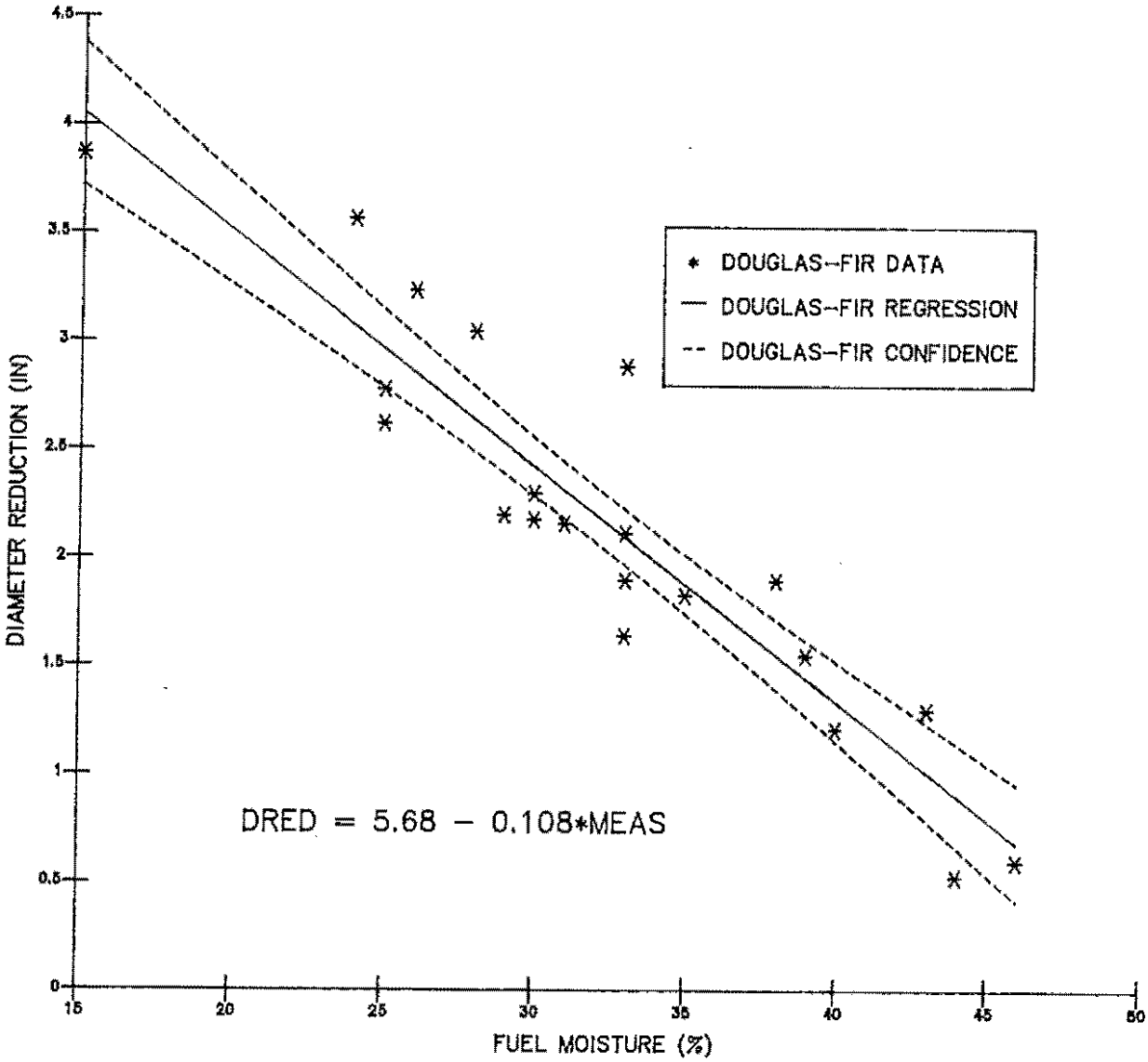


Figure 1. Regression of unit-average large fuel diameter reduction on measured fuel moisture. Data was collected from Douglas-fir and western hemlock prescribed burns located in western Oregon and western Washington. Confidence bands are at the 95 percentile and are for the regression line.

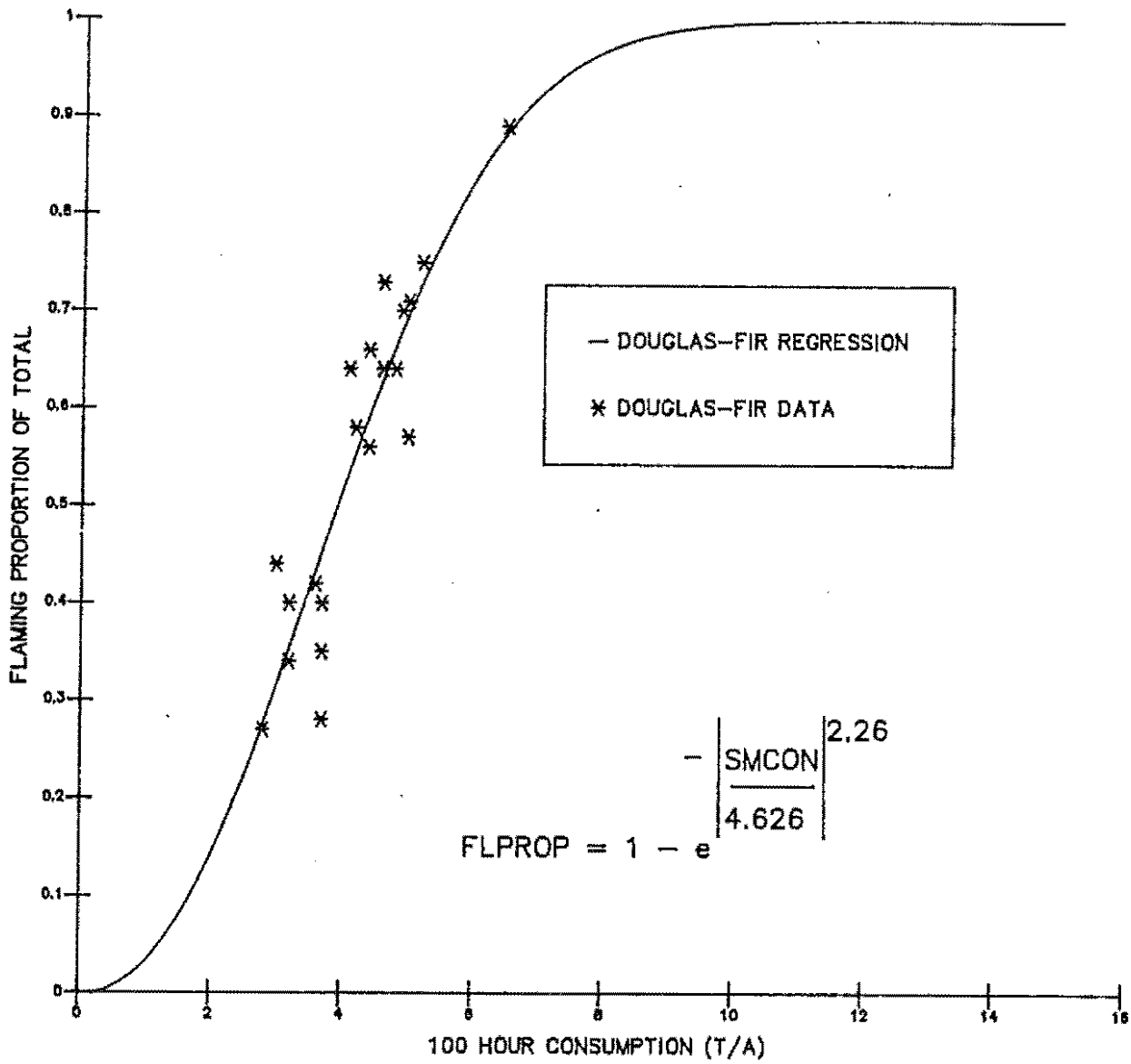
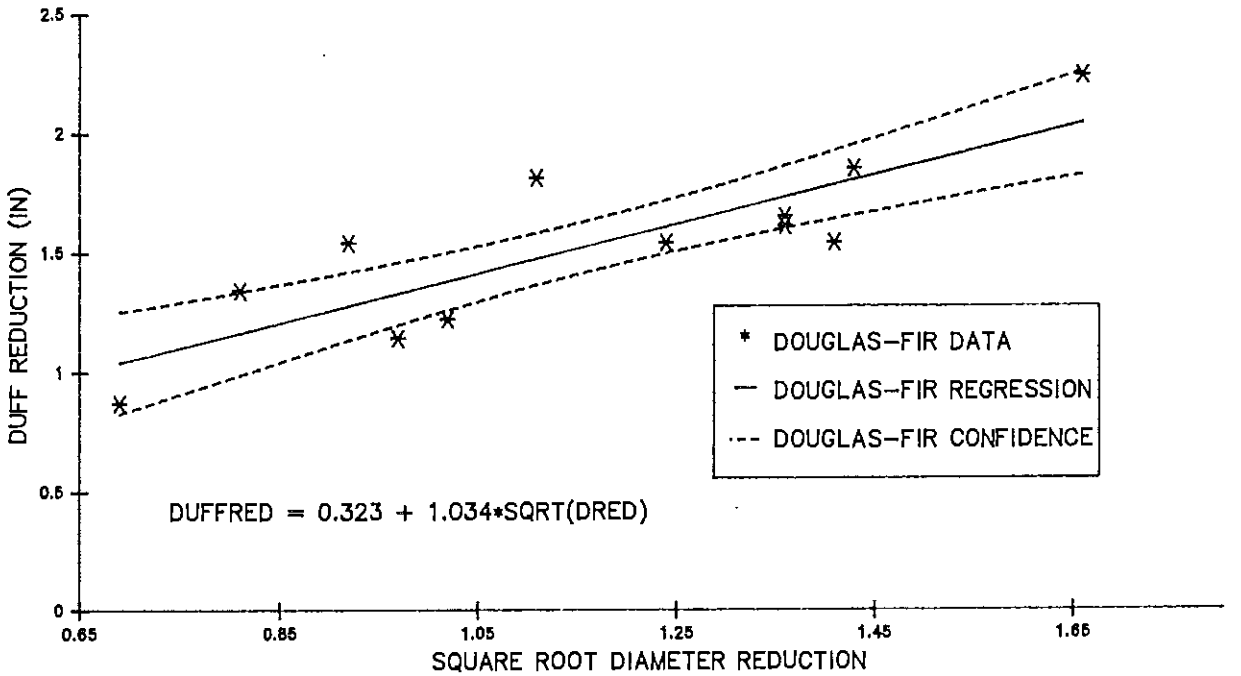


Figure 2. Regression of flaming proportion of large fuel consumption on consumption of 1- to 3-inch diameter woody fuels. Data was collected from Douglas-fir and western hemlock prescribed burns located in western Oregon and western Washington.



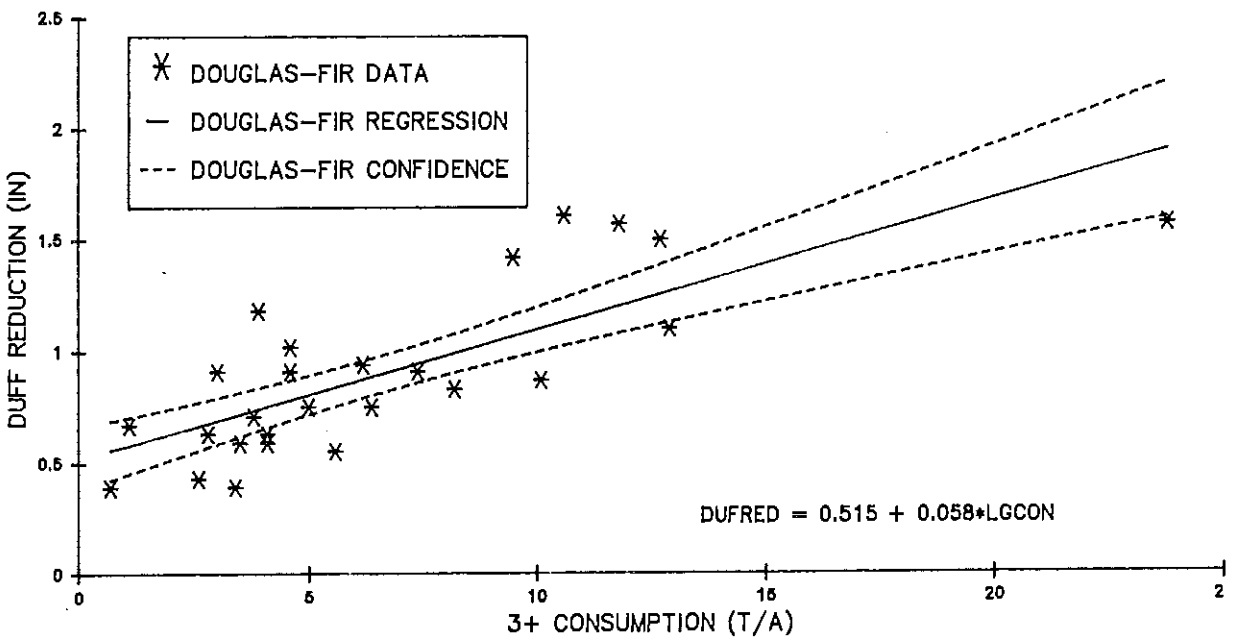


Figure 3. Regression of unit-average duff reduction on large fuel consumption for units burned with less than 25 days since significant rain and greater than or equal to 25 days since significant rain. Data was collected from Douglas-fir and western hemlock burns located in western Oregon and western Washington. Confidence bands are at the 95 percentile and are for the regression line.

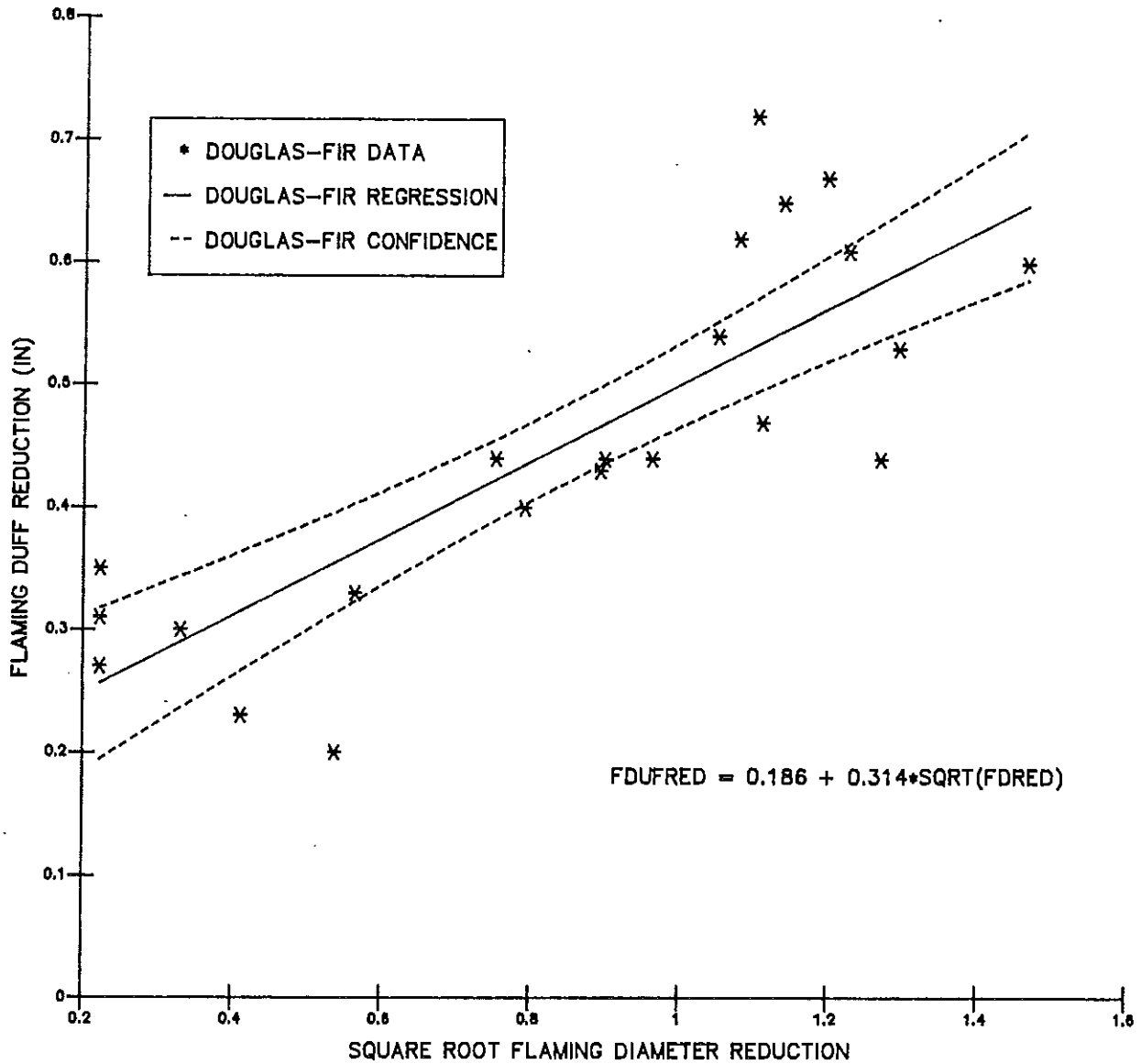


Figure 4. Regression of flaming duff reduction on flaming diameter reduction of the large fuels. Data was collected from Douglas-fir and western hemlock prescribed burns located in western Oregon and western Washington. Confidence bands are at the 95 percentile and are for the regression line.

Fuel consumption equations for Douglas-fir and western hemlock sites have been distributed in easy-to-use nomographs. The nomographs are in use by most forest managers in Oregon and Washington and are the basis for Oregon's Smoke Management Reporting System.

Table 1. Fuel consumption regression equations developed for western Oregon and western Washington prescribed fires in the Douglas-fir and western hemlock cover type. The equation includes (1) unit-average diameter reduction (DRED, inches) based on fuel moisture content (MEAS, percent); (2) flaming stage proportion (FPROP) based on 1- to 3-inch diameter woody fuel consumption (SMCON, tons/acre); (3) unit average duff reduction (DUFRED, inches) based on large fuel consumption (LGCON, tons/acre) and large-fuel diameter reduction (DRED, inches); and (4) flaming duff reduction (FDUFRED, inches) based on flaming diameter reduction of large fuels (FDRED, inches).

EQUATION		N^a	r^{2a}	$s_{y.x}{}^c$
				-Inches-
DRED	= 5.68 - 0.108 MEAS	21	0.86	0.340
FPROP	= 1 - EXP(-ABS(SMCON/4.626))**2.26	20	0.81	0.006
DUFRED	= 0.515 + 0.058 LGCON	26	0.59	0.246
DUFRED	= 0.323 + 1.034 SQRT(DRED)	12	0.70	0.207
FDUFRED	= 0.186 + 0.314 SQRT(FDRED)	22	0.68	0.087

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

The fuel consumption equations have been incorporated into a user-friendly program, called **CONSUME**, for use by forest managers. The fuel consumption equations have also been placed into the Emissions Production Model (EPM) (Sandberg and Peterson 1984) which is used in the emissions inventory process for Oregon and Washington (Ottmar 1986).

The only other large research effort to develop fuel consumption models in fuel types common to Oregon and Washington was by Brown and others (1985). Brown developed total woody fuel and duff consumption models for Montana activity

fuels in the larch/Douglas-fir cover type. Large, woody fuel consumption was best correlated with preburn loadings. Moisture content of the lower duff was the best predictor for duff reduction. This variable is difficult to measure and predict. No work was done on fuel consumption by combustion stage in this effort.

Thousands of acres of pile burns are accomplished each year in Washington and Oregon. Very little research has been completed on the preburn characterization and consumption of piled slash. Little (1982) characterized preburn loading of woody debris piles based on the shape and size of nine small piles constructed of unmerchantable logging debris. Fuel consumption models for piled slash are non-existent. Current smoke-management reporting systems assume 90- to 100-percent consumption, with most the combustion occurring during flaming stage.

It is evident from the literature that very limited or no research has been undertaken to model consumption of western-forest woody fuels. Douglas-fir and western hemlock are the only fuel types having had extensive research. Prior knowledge enabled quantitative analysis of mitigation that is possible through utilization of Douglas-fir and western hemlock broadcast burns only. Analysis of the mitigation potential for other cover types, such as hardwoods, long-needled pine, and mixed conifer, were qualitative. Table 2 describes prior knowledge of the consumption of live fuels, woody fuels, and duff by cover type and fuel-bed component for forest activity fuels. The cover types are types commonly found in the 11 western states where much of the prescribed burning activity occurs.

Table 2. Prior knowledge of fuel consumption by cover and burn type, and by fuel-bed component, for activity fuels. The level of burning activity for each cover type component have been estimated.

Cover Type	Burn Type	Fuel Consumption By Fuel Bed Component				Burning Activity
		Live	Small	Large	Duff	
Douglas-fir/ Western hemlock	broadcast	4	1	1	1	H
	piled	-	3	3	3	H
West-coast hardwood	broadcast	4	3	3	3	H
	piled	-	3	3	3	L
Mixed conifer*	broadcast	4	3	3	3	H
	piled	-	3	3	3	H
Ponderosa pine	broadcast	4	3	3	3	H
	piled	-	3	3	3	H
Lodgepole pine	broadcast	4	3	3	3	H
	piled	-	3	3	3	H
Rocky Mountain hardwood	broadcast	4	3	3	3	L
	piled	-	3	3	3	L
Juniper	broadcast	4	2	2	2	H
	piled	-	3	3	3	L
Redwood	broadcast	4	3	3	3	M
	piled	-	3	3	3	M
Chaparral	broadcast	4	3	-	-	L
	piled	-	-	-	-	L

1 -- Measured and/or modeled.
2 -- Sampled and/or inferred.
3 -- Know qualitatively.
4 -- No knowledge.

H - High
M - Medium
L - Low

* Mixed conifer refers to mixture of species including western larch, Douglas-fir, grand fir, lodgepole pine, subalpine fir, and western white pine.

The level of knowledge for predicting fuel consumption has increased considerably because of this Interagency Agreement. In most cases, there was no knowledge, or a limited amount of knowledge, about fuel consumption in the long-needled pine and mixed conifer stands and west-coast hardwood forests before this study was initiated. We are now able to model fuel consumption for prescribed burns of these fuels (see conclusion section).

3.0 OBJECTIVES

The overall objective of this portion of the investigation was to assess large, woody fuel and duff consumption by combustion stage during hardwood conversion prescribed burns in western Oregon and Washington and long-needled pine, mixed conifer prescribed burns in eastern Oregon and Washington. Specific objectives included:

1. Measure large, woody fuel and duff consumption by fire stages during 9-12 hardwood conversion prescribed burns in western Oregon and western Washington

2. Measure large, woody fuel and duff consumption by fire stages during 9-12 long-needled pine and mixed conifer prescribed fires in eastern Oregon and eastern Washington.

3. Develop woody fuel and duff consumption models for hardwood and long-needled pine, mixed conifer cover types.

4.0 METHODS

Consumption of large fuels was measured as diameter reduction (which was converted to volume reduction) from 40 randomly chosen logs, 3 to 9 inches in diameter. The logs intersected fuel-inventory transect lines established at each of 18 permanent plots. A fuel-moisture sample was obtained from both the large and small end of each log immediately before the burn. Wires with numbered tags for log identification were tightly wrapped around the logs before burning and were cinched up after burning; the exposed wire lengths were then measured to determine diameter reduction.

Twenty of the logs were permanently elevated 12 to 14 inches off the ground on steel stands so that the logs would not collapse during fuel-bed consumption, which would result in its being partially consumed in the smoldering stage. The average diameter reduction of these elevated logs represents diameter reduction during the flaming stage. Average diameter reduction of the 20 logs not elevated provided an estimate of total diameter reduction in both the flaming and smoldering stages. By adjusting the diameter reduction of the suspended and unsuspended logs for differences in average fuel moisture between the two groups, a flaming proportion could be calculated and compared to independent variables.

Duff consumption was measured as duff-depth reduction according to procedures adapted from Beaufait and others (1977). Eleven metal and five ceramic duff pins were inserted flush with the duff layer around each permanent plot. Duff included the fermentation layer and the humus layer.

Ceramic tiles were coated with a heat-sensitive paint. The heat-sensitive paint would melt at 600° C, which is the general temperature as reported in literature where the combustion stage changes from flaming to smoldering. The length of melted paint could be measured in the lab to determine flaming-stage reduction of duff. Total duff reduction was determined in the field by measuring the exposed length of the ceramic and metal duff pins.

Several other independent variables were measured on each burn. Loadings of large fuels for each unit were estimated from a planar intersect inventory (Brown 1974). Sampling density consisted of 50-foot line transects located at 80 semi-permanent points on a systematic grid. Small fuels were measured before and after burning, along the 50-foot transect lines established at each of the 18 permanent plots.

Average duff-moisture content for each unit was calculated from 36 moisture samples. The samples were collected from around each duff-consumption plot. If a distinct dry layer was found in the duff profile, a sample from each layer was collected and dry-layer depth was recorded. All samples were oven dried at 162 °F, for 96 hours.

The nearest representative weather station was used to monitor environmental conditions before burning each unit. Ignition of the units occurred when time since the last soaking rainfall (greater than or equal to 0.50 inch) was between 3 and 60 days, which allowed enough time to nearly complete combustion of fine fuels without the duff's burning independently of woody fuels.

Single- and multiple-regression techniques were used to measure the relation between large-fuel and duff consumption and several independent variables for hardwood and east-side mixed conifer and long-needled pine data. Analysis of covariate techniques (Snedecor and Cochran 1971) were used to compare hardwood and east-side algorithms with algorithms developed for westside Douglas-fir and western hemlock prescribed burns (Sandberg and Ottmar 1983, Ottmar and others 1985) when appropriate. All tests were performed using the SPSS/PC+ V2.0 package system (Norusis 1988). All tests were completed at the 90- and 95-percent confidence levels.

5.0 RESULTS

Twenty hardwood and 20 east-side conifer units were inventoried and burned during 1985 and 1986, exceeding our commitment by 16 units. Tables 3 through 6 display preburn fuel information and fuel consumption data from all units burned during 1985 and 1986 under this agreement.

5.1 Preburn Fuel--Hardwood Units

Large fuel loadings and duff depths varied between units and spanned the range characteristics of hardwood clearcut units harvested for site conversion in western Washington and Oregon. Loadings of large fuels on hardwood units varied from 27 tons per acre on a tanoak conversion unit utilized only for firewood, to 3.7 tons per acre on an alder unit used for timber and firewood. The mean large-fuel loading for all hardwood units measured in the study was 11.5 tons/acre. Average duff depth generally ranged from 0.75, to over 5 inches.

Table 3. Unit and fuel data summary for westside hardwood units.

Unit	State	Forest	Species	Date Burned	Preburn Fuels: Large Fuel Tons/Ac	Preburn Fuels: Duff Inches	Fuel Moisture: Large Fuel Percent	Fuel Moisture: Upper Duff Percent	Fuel Moisture: Lower Duff Percent	Days Since Rain***
Wildmoore	OR	Siskiyou	Hardwood	02-27-85	--	--	48	--	--	<25
Eagle Feather #5	OR	Siskiyou	Hardwood	03-15-85	24.8	--	30	--	--	<25
Eagle Feather #4	OR	Siskiyou	Hardwood	05-01-85	27.1	--	32	--	--	<25
Peterson Creek	WA	Champion*	Hardwood	06-27-85	8.3	.75	31	21	311	<25
Upper Ten 110 #2	OR	Siuslaw	Hardwood	07-02-85	8.4	1.69	60**	18	259	>25
Gauldy Hebo A (Tower)	OR	Siuisaw	Hardwood	07-15-85	10.4	5.28	29	23	252	>25
Elder Alder A (Tower)	OR	Siuslaw	Hardwood	07-18-85	5.8	2.13	55**	16	272	>25
Elder Alder B	OR	Siuslaw	Hardwood	07-24-85	3.7	3.11	55**	18	224	>25
Upper Ten 110 #3	OR	Siuslaw	Hardwood	08-22-85	11.2	2.17	48	34	118	>25
Victoria 2 (Tower)	WA	Pilchuck*	Hardwood	09-25-85	8.2	.91	31	31	126	<25
Gauldy Hebo A	OR	Siuslaw	Hardwood	09-28-85	5.5	1.69	35	31	177	<25
Cherry Alder A	OR	Siuslaw	Hardwood	09-28-85	13.2	1.38	42	37	227	<25
Church	WA	Pilchuck*	Hardwood	10-01-85	11.0	1.34	28	35	156	<25
Tilton 27	WA	Champion*	Hardwood	10-02-85	6.0	.94	31	--	--	<25
Cedar Pollard C	OR	Siuslaw	Hardwood	06-12-86	10.2	1.81	30	--	--	<25
Cedar Pollard C (Tower)	OR	Siuslaw	Hardwood	06-12-86	4.1	2.91	18	18	261	<25
Limestone Boulder G-4	OR	Siuslaw	Hardwood	09-03-86	19.3	1.65	28	11	195	>25
Limestone Boulder G-3	OR	Siuslaw	Hardwood	09-04-86	16.4	1.14	35	16	--	>25
Limestone Boulder G-1	OR	Siuslaw	Hardwood	09-05-86	14.9	2.17	28	--	--	>25
Limestone Boulder G-2	OR	Siuslaw	Hardwood	10-10-86	9.2	.83	45	--	--	<25

Dashed line means data was not collected.
*Private Timber Company
**Large, woody fuels were uncured.
***Rain of 0.50 inch

ble 4. Fuel consumption summary for westside hardwood units.

	1-3 Inch	Large Woody Fuel Consumption				Duff Consumption	
	Fuel Consumption	Diameter Reduction	Fuel Consumption	Flaming Diameter Reduction	Flaming Proportion of Total	Duff Depth Reduction	Flaming Duff Depth Reduction
it	Tons/Ac	Inches	Tons/Ac	Inches		Inches	Inches
ldmoore	**	**	**	**	**	**	**
gle Feather #5	11.3	2.78	21.4	--	--	--	--
gle Feather #4	6.6	2.63	21.7	--	--	--	--
terson Creek	13.2	2.41	5.9	2.18	1.00	.63	.02
per Ten 110 #2	4.3	1.31	3.5	.57	.50	1.38	.42
aldy Hebo A (Tower)	3.9	3.09	8.5	--	--	1.97	.63
der Alder A (Tower)	3.2	.97	1.8	.25	.20	1.26	.39
der Alder B	3.2	1.14	1.4	.32	.24	1.77	.58
per Ten 110 #3	4.4	2.83	6.9	2.25	.60	1.89	.68
ctoria 2 (Tower)	4.9	2.24	6.2	1.40	.68	1.06	.52
uldy Hebo A	.9	2.51	3.7	1.40	.71	.67	.21
erry Alder A	5.0	1.28	2.9	1.01	.60	.47	.23
urch	5.9	1.30	4.2	--	--	.63	.21
lton 27	5.9	1.56	2.7	1.06	.54	.67	.45
dar Pollard C	10.4	2.20	5.1	1.55	.92	1.18	.43
dar Pollard C(Tower)	11.9	1.67	2.8	--	--	1.38	--
mestone Boulder G-4	6.4	2.10	10.4	--	--	1.30	--
mestone Bullder G-3	5.3	1.60	7.9	--	--	1.34	--
mestone Boulder G-1	4.7	1.98	8.5	--	--	1.77	--
mestone Boulder G-2	.8	.05	.1	--	--	.16	--

shed line means data was not collected.
Fine fuels were too wet and much of the area was unburned.

Table 5. Unit and fuel data summary for eastside units.

Unit	State	Forest	Species	Date Burned	Preburn Fuels: Large Fuel Tons/Ac	Preburn Fuels: Duff Inches	Fuel Moisture: Large Fuel Percent	Fuel Moisture: Upper Duff Percent	Fuel Moisture: Lower Duff Percent	Days Since Rain***
Boot #2	WA	Okanogan	Long-need.	06-01-85	26.1	1.3	39	29	144	<25
Surprise 18	WA	Colville	Conifer	06-11-85	25.1	1.5	37	37	185	<25
Boot #1	WA	Okanogan	"	06-14-85	24.9	1.77	36	41	144	<25
Sugarloaf (Tower)	WA	Wenatchee	"	10-04-85	22.3	2.8	24	22	97	>25
Westridge #14	OR	Deschutes	"	03-28-86	9.6	--	76**	23	117	<25
Westridge #15	OR	Deschutes	"	03-31-86	18.9	.94	72**	31	100	<25
Pathfinder #1	OR	Mt. Hood	"	04-24-86	6.3	1.10	40	12	150	<25
Pathfinder #2	OR	Mt. Hood	"	04-24-86	7.7	1.02	41	9	94	<25
Five Mile Creek	WA	Wenatchee	"	04-29-86	25.8	1.89	38	36	174	<25
Annebelle	OR	Deschutes	"	05-16-86	--	1.34	44	16	54	<25
LoLo	OR	Deschutes	"	05-22-86	7.9	--	38	--	--	<25
LoLo Towers I	OR	Deschutes	"	05-22-86	10.4	--	42	--	--	<25
Bold 1	WA	Colville	"	05-28-86	21.7	2.40	32	49	200	<25
Winston #5	WA	Colville	"	06-02-86	20.8	1.26	29	12	183	<25
LoLo Towers II	OR	Deschutes	"	06-04-86	9.1	--	39	--	--	<25
Winston #8	WA	Colville	"	06-26-86	19.8	1.18	20	13	168	<25
Summit Lodgepole	WA	Colville	"	07-31-86	30.6	2.01	29	20	175	<25
North Corner 17 (Tower I)	WA	Wenatchee	"	10-02-86	6.7	--	33	--	--	<25
North Corner 17 (Tower II)	WA	Wenatchee	"	10-05-86	6.0	--	32	--	--	<25
West Iron #14	WA	Wenatchee	"	10-13-86	22.5	2.13	25	112	143	<25

Dashed line means data was not collected.
**Large, woody fuels were uncured.
***Rain of 0.25 inch

able 6.--Fuel consumption summary for eastside units.

nit	1-3 inch	Large Woody Fuel Consumption				Duff Consumption	
	Fuel Consumption Tons/Ac	Diameter Reduction Inches	Fuel Consumption Tons/Ac	Flaming Diameter Reduction Inches	Flaming Proportion of Total	Duff Depth Reduction Inches	Flaming Duff Depth Reduction Inches
oot #2	4.1	1.76	12.3	.91	.59	.79	.28
urprise 18	4.4	.93	7.8	.93	.42	.51	.22
oot #1	5.6	1.29	9.8	1.00	.52	.91	.30
ugarloaf (tower)	3.8	2.99	15.9	2.78	.95	1.85	.61
estridge #14	4.2	.64	2.3	.25	.24	--	--
estridge #15	1.9	.48	2.0	.15	.08	.79	--
athfinder #1	6.4	2.01	4.0	1.14	.90	1.02	--
athfinder #2	6.8	2.08	5.0	1.07	1.00	.91	.26
ive Mile Creek	5.8	1.90	13.8	1.21	.63	.94	.34
nnebelle	3.2	.63	1.2	--	--	.79	--
oLo	3.6	.99	2.8	.44	.92	--	--
oLo Towers I	1.9	.47	1.9	--	--	--	--
old I	5.0	2.70	12.0	1.46	.50	.87	.22
inston #5	3.7	1.06	7.1	1.03	1.00	.71	--
oLo Towers II	2.6	.55	1.8	--	--	--	--
inston #8	2.8	.73	3.7	.65	.98	.63	.21
ummit Lodgepole	4.6	2.92	23.2	3.05	.94	1.42	.93
orth Corner 17 (tower I)	3.4	.95	2.2	--	--	--	--
orth Corner 17 (tower II)	4.1	1.21	2.8	--	--	--	--
est Iron #14	3.5	2.19	12.6	1.31	.51	1.02	.25

ashed line means data was not collected.

5.2 Preburn Fuel--East-side Units

Since the units selected for the study ranged from central Oregon to northeast Washington, with a variety of yarding specifications, large fuel loadings and duff depths spanned a wide range characteristic of east-side units harvested for timber. Loadings of large fuels ranged from 30.6 tons per acre on a lodgepole unit (harvested to an unspecified yarding specification with no access for fuel wood collection), to 6.0 tons per acre on a ponderosa pine unit (harvested to a minimum specification of removing all sound material greater than 6 inches in diameter and 6 feet in length). The mean loading for the large fuel on all east-side units inventoried was 16.1 tons per acre.

Duff depth was more shallow than on the westside hardwood units and ranged from 1 to nearly 3 inches.

5.3 Fuel Moisture--Hardwood Units

Hardwood units were burned under a variety of moisture regimes that adequately covered the moisture content range generally found during the burning season of spring through early autumn. Three of the units were burned shortly after harvest was completed, which resulted in uncured fuels.

The measured moisture contents varied from 48 percent on a unit burned in February, to 18 percent on a unit burned in summer. Measured large-fuel moisture content from the three uncured units ranged from 55 to 60 percent. Measured moisture content of the duff ranged from nearly 300 percent in the lower, wet layer to less than 15 percent in the upper, dry layer.

5.4 Fuel Moisture--East-side Units

The east-side units were burned from early March to mid-October. This adequately covered the moisture regimes under which most forest managers burn in eastern Washington and eastern Oregon. Within the study areas, average moisture content of large fuels ranged from 20 to 44 percent on the cured units. Measured fuel-moisture content on two units considered uncured ranged from 72 to 76 percent. Measured moisture content of the duff layers ranged from 54 to 200 percent in the lower, wet layer, to 9 to 112 percent in the upper, dry layer.

5.5 Fuel Consumption--Hardwood Units

Diameter reduction of large, woody fuels in the 19 hardwood units where fuel consumption data could be measured ranged from 0.05 inch on a unit with brush and wet fuels, to 3.09 inches on a unit burned where the fuels were dry. Flaming diameter reduction ranged from 0.25 inch to 1.55 inch.

Duff consumption varied from a reduction of 1.97 inches on a unit burned under dry, windy conditions, to 0.16 inch on a unit with preburn duff depth of less than 1 inch. Flaming duff consumption ranged between 0.02 inch to 0.68 inch.

One of the units was burned in February, with the small fuels having a fuel-moisture content over 25 percent. A continuous burn did not occur and, therefore, consumption data was not collected.

5.6 Fuel Consumption--East-side Units

Diameter reduction of 20 long-needled conifer units on the eastside ranged from 0.47 inch on a flat unit (which had very little duff) that was burned shortly after snowmelt, to 2.99 inches on a very dry unit that was burned in the fall. Flaming diameter reduction ranged from 0.15 inch to 3.05 inches on a helicopter ignited unit. Consumption of duff ranged from 0.51 inch to 1.85 inches. Flaming duff consumption ranged from 0.21 inch to 0.93 inch.

6.0 ANALYSIS AND DISCUSSION

6.1 Fuel Consumption Modeling--Hardwoods

6.1.1 Large, woody fuels

Average diameter reduction per unit (DRED, inches) was regressed on several independent variables. Diameter reduction was best correlated with large-fuel moisture (LGFM, percent). Linear regressions of unit-average moisture content for large fuels were slightly significant; however, no improvement could be gained by adding other independent variables or by stratifying the data (table 7). Range of fuel moistures was very limited and a poor r^2 was noted. A larger range of fuel moisture contents would have improved the r^2 but that would have required several additional units be burned under extreme fuel-moisture conditions.

Table 7. Regression equation for unit-average diameter reduction (DRED, inches) based on measured large-fuel moisture content (MEAS, percent) for hardwood (HD) and Douglas-fir/western hemlock (DF/H) units. All regression equations are at the 95-percent confidence level.

SPECIES	EQUATION	N[a]	r^{2b}	$s_{y.x}$[c]
				-Inches-
HD	DRED = 4.49 - 0.072 MEAS	12	0.28	0.47
DF/H	DRED = 5.68 - 0.108 MEAS	21	0.86	0.34

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

Several of the 20 hardwood units were removed from the data set. Three of these units had large-fuel moisture values between 50 and 60 percent and were considered uncured. They showed more consumption than would have been expected under cured moisture conditions in a conifer unit. This may be due in part to the characteristics of live fuel moisture within the uncured slash. A current study is investigating the drying and wetting of uncured slash and its effects on prescribed fire (Ottmar 1987).

In addition to the three units with uncured fuels, five units measured for woody-fuel consumption in the hardwood cover type were removed from the data set. One unit had an insufficient number of logs greater than 3 inches in diameter and a valid data base was not collected. One unit sustained surface winds which increased glowing combustion during the smoldering stage and more diameter reduction took place than was accounted for by fuel moisture. Two units were burned when the fine fuels were very wet and fuel consumption was spotty. Finally, one study site was burned without notification and no fuel moisture samples were collected.

Analysis of the large-fuel-consumption data indicates that a simple, thermodynamic process occurs during a prescribed burn. During the combustion process, small fuels ignite larger fuels and the larger fuels will consume until quenched by internal fuel moisture. If the large fuels are uncured and fuel-moisture values are greater than 50 percent, preliminary research (Ottmar 1987) has shown that these fuels appear to be more combustible than cured slash at the same high fuel-moisture.

Linear regression of fuel moisture on diameter reduction for the hardwood units was examined to see if it was the same as the Douglas-fir and western hemlock regression. The hypothesis of homogeneous variance among populations, common slope, and common y-intercept are not rejected. The two equations are regarded as the same and the Douglas-fir and western hemlock can be used to estimate diameter reduction for hardwood prescribed burns (figure 5).

Ten of the 20 hardwood units were measured for flaming woody-fuel consumption. The proportion of large, woody fuels that were consumed during the flaming stage were shown to be nonlinearly dependent upon consumption of woody fuels 1- to 3-inches in diameter (table 8), which seems to follow thermodynamic reasoning. Small fuels consume mostly during the flaming stage until there are too few pieces to interact. Large fuels consume during the flaming stage based on the amount of consumption of small fuels.

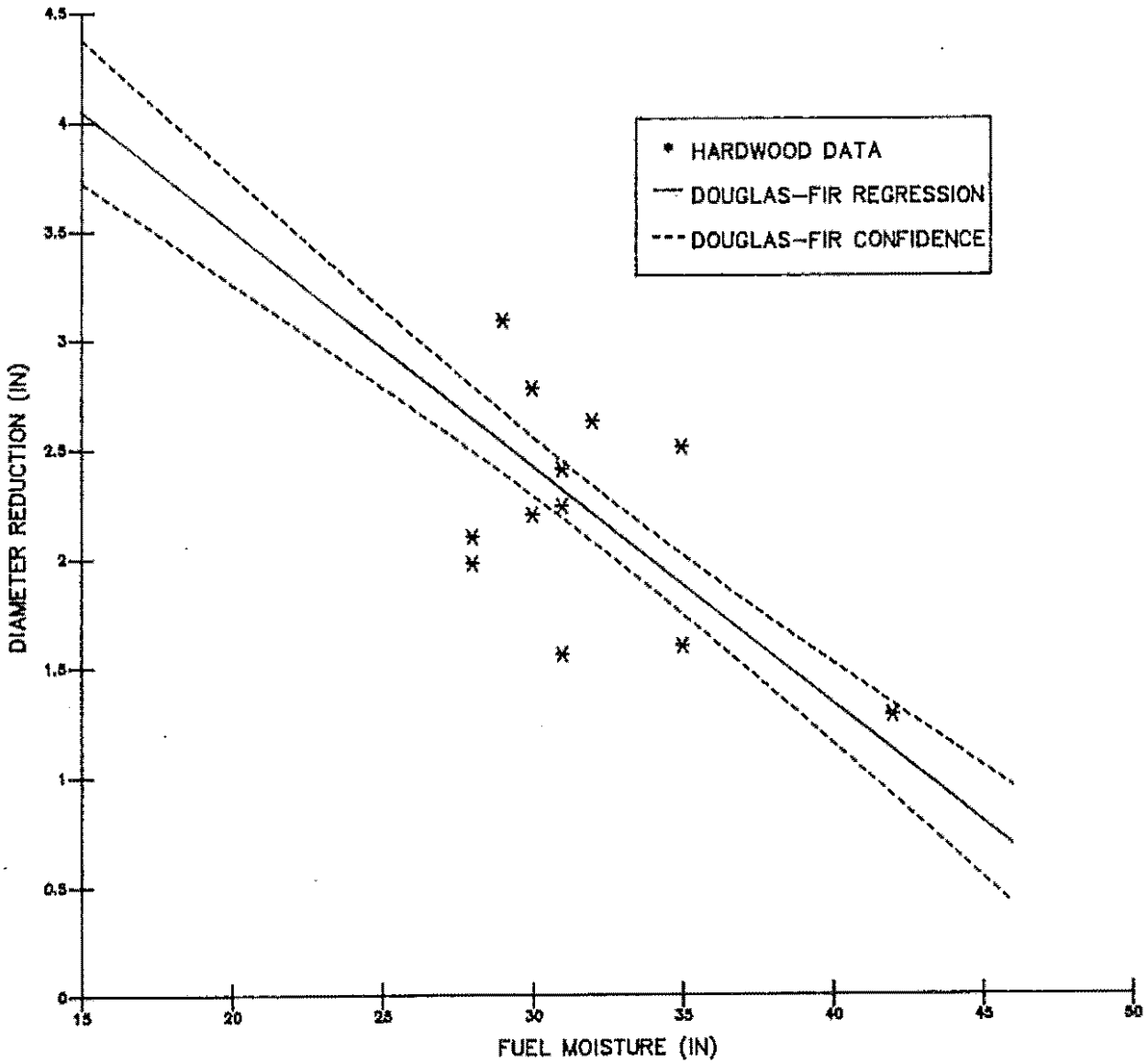


Figure 5. Large fuel diameter reduction plotted against measured fuel moisture for hardwood slash burns. The solid regression line represents fuel moisture and fuel diameter reduction relationship established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression line.

Table 8. Regression equation for flaming proportion (FPROP) based on 1- to 3-inch woody fuel consumed (SMCON, tons/acre) for hardwood (HD) and Douglas-fir/western hemlock (DF/H) units. All regressions are significant at the 95-percent level.

SPECIES	EQUATION	N[a]	r^{2}[b]	$s_{y.x}$[c]
				-Inches-
HD	FPROP = 1 - EXP(-ABS(SMCON/5.345))**2.26	7	0.85	0.007
DF/H	FPROP = 1 - EXP(-ABS(SMCON/4.626))**2.26	20	0.81	0.006

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

This relationship is similar to analysis computed on woody-fuel consumption for Douglas-fir and western hemlock fuel types (figure 6), although slightly less fuel is consumed during the flaming stage per ton of 1- to 3-inch material consumed. Two of the 10 units were removed from this data set because the fuels were uncured; one unit was removed because fine fuels were very wet and the burn was not continuous.

Although fuel consumption of the 1- to 3-inch material is very difficult to predict, small fuels can be assumed to consume completely under most burning scenarios. Only if the prescribed burn occurs during earlier, spring-like conditions will this assumption be inaccurate. Fuel consumption under spring-like conditions are currently being investigated with support from the Siuslaw, Willamette, and Olympic National Forests, and from private industry.

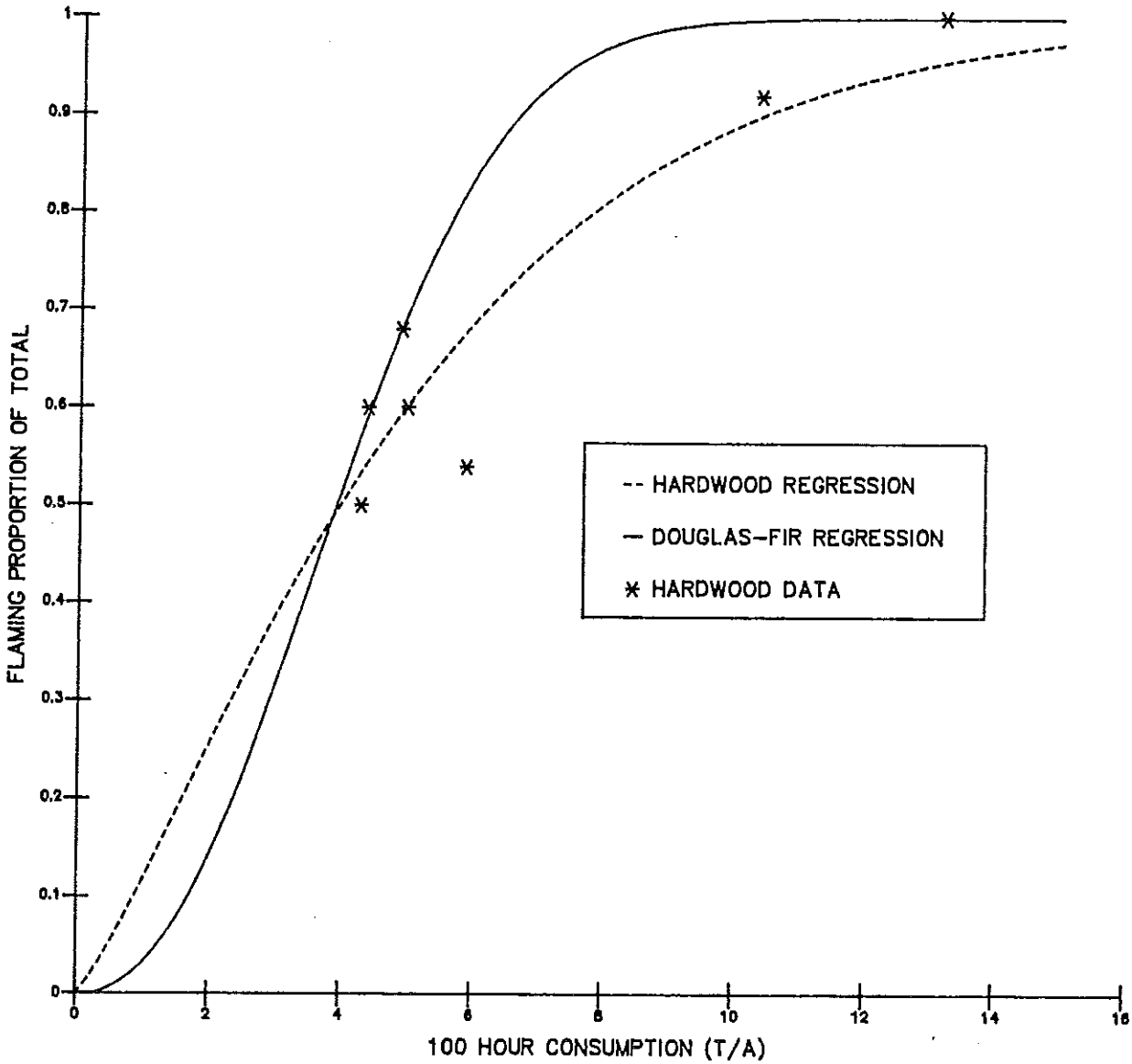


Figure 6. Flaming proportion of large fuel consumption plotted against consumption of 1- to 3-inch diameter woody fuels for hardwood prescribed burns. Regression lines are displayed for hardwood and Douglas-fir/western hemlock units.

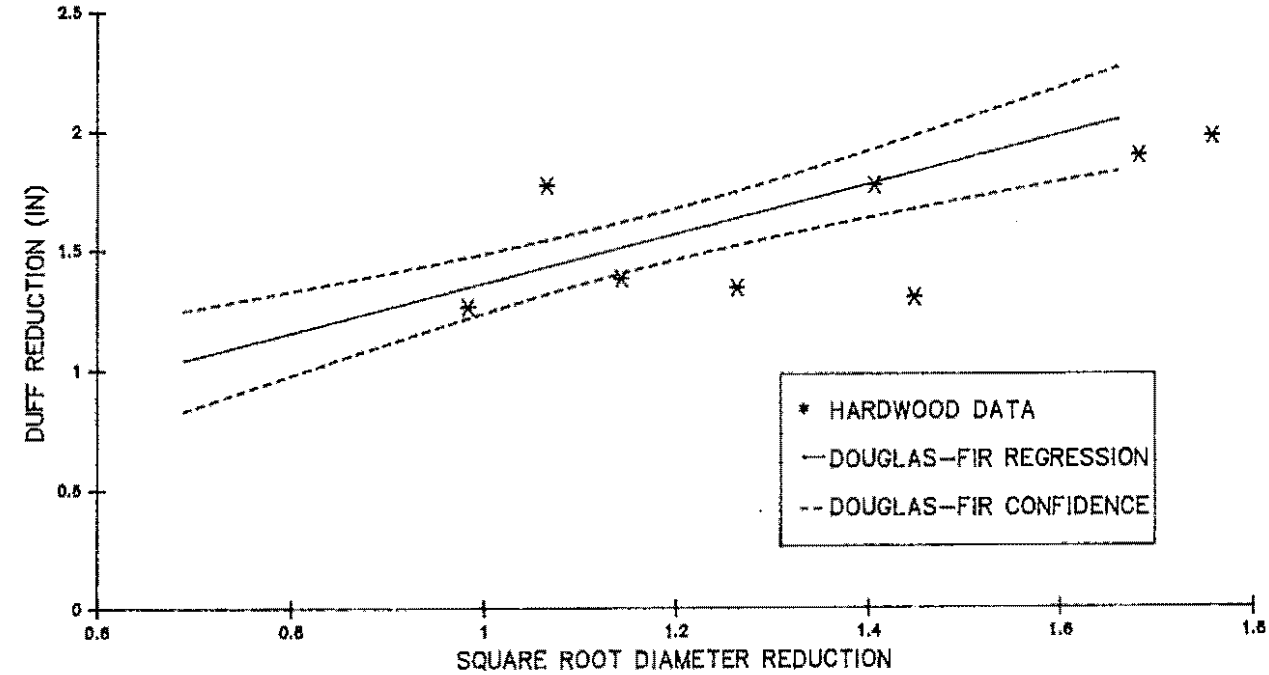
6.1.2 Duff Consumption

Average duff consumption was related linearly to large fuel consumption when the humus layer was moist (less than 25 days since significant rain fall of .50 inch) and diameter reduction when the humus layer is dry (greater than or equal to 25 days since significant rainfall of .50 inch) (table 9). Even though the large fuel consumption measured was in a narrow range, the relationship was similar to an analysis completed on duff consumption in Douglas-fir and western hemlock fuel types (figure 7). Two units were removed from the data set in figure 4 because of wet fine-fuel conditions and an insufficient number of logs that were greater than 3 inches in diameter, which would make the unit-average diameter reduction invalid.

Table 9. Regression equations for unit-average duff reduction (DUFRED, inches) based on large-fuel consumption (LGCON, tons/acre) and large-fuel diameter reduction (DRED, inches) for hardwood and Douglas-fir/western hemlock units. All regressions are significant at the 95 percent level.

SPECIES	EQUATION	N[a]	r^{2b}	$s_{y.x}$[c]	Time since rain
				-(Inches)-	-(Days)-
HD	DUFRED = 0.263 + 0.113 LGCON	7	0.37	0.22	0-24
HD	DUFRED = 0.684 + 0.670 SQRT(DRED)	8	0.41	0.24	25-60
DF/H	DUFRED = 0.515 + 0.058 LGCON	26	0.59	0.25	0-24
DF/H	DUFRED = 0.323 + 1.034 SQRT(DRED)	12	0.70	0.20	25-60

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.



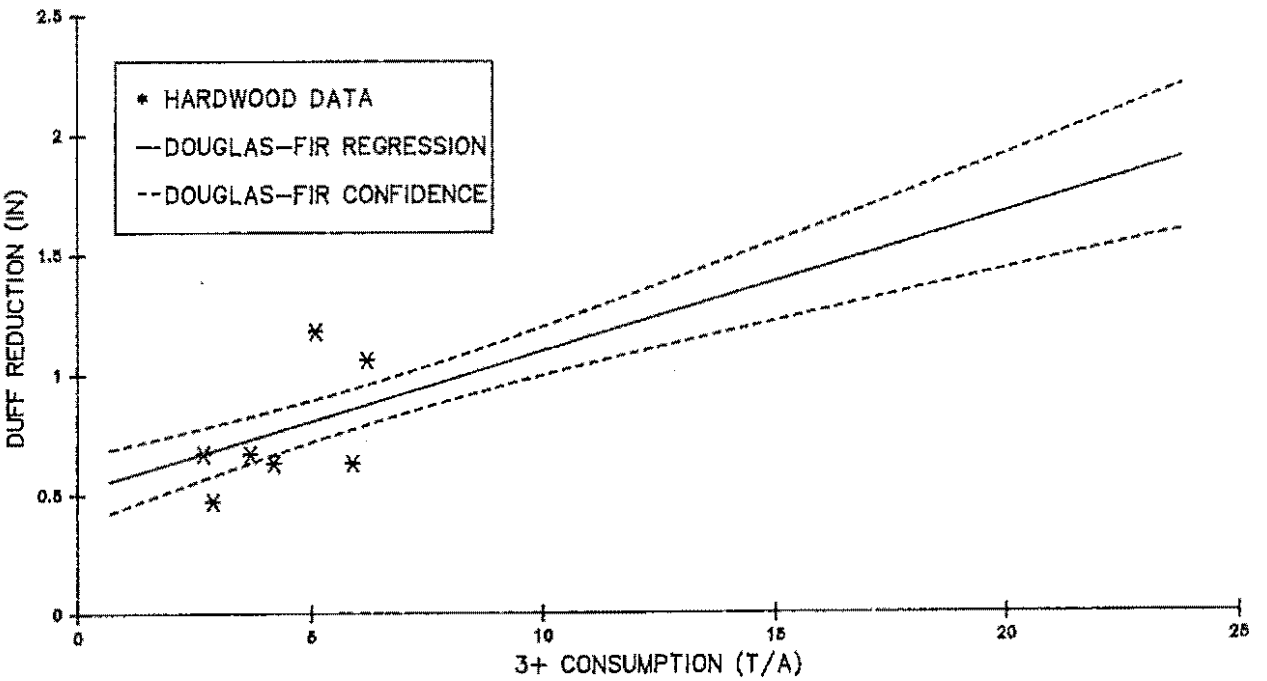


Figure 7. Duff reduction plotted against large fuel consumption for hardwood units burned with less than 25 days since significant rain and greater than or equal to 25 days since significant rain. The solid regression line represents large fuel consumption and duff reduction relationship established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression lines.

The thermodynamic process involved during consumption of duff is very evident. When duff is wet (days since rain is less than 25), duff reduction was dependent on total heat load supplied by the combustion of large fuels. The duff will be dried to a depth that is dependent on large fuel consumption and duff will consume during smoldering stage to the depth at which it dried.

When duff profile was dry (days since rain greater than or equal to 25 but less than 60), duff reduction was dependent on the duration of fire, as determined by the diameter reduction of large fuels. Under drier duff conditions, a dry layer is formed from atmospheric drying, which acts as an insulating layer. The duration of heat rather than total heat load becomes the critical variable which controls the amount of duff consumption.

If days since rain is greater than 60 days, duff burns independent of woody fuel consumption. No data has been collected for this situation and there is no predictive equation available. Forest managers rarely burn under extreme drought situations when the duff is very dry.

Analysis of co-variance comparisons of hardwood and Douglas-fir/western hemlock regression equations for less than 25 days and greater than or equal to 25 days since significant rainfall indicated no significant differences. The Douglas-fir and western hemlock regressions established for duff consumption can be used for predicting duff consumption in hardwood prescribed fires.

To compare with the Douglas-fir and western hemlock relationship, flaming duff reduction was regressed against diameter reduction of large woody fuels for hardwood prescribed burns (figure 8). No relationship between these variables seemed to exist with an r^2 close to zero (table 10). Additional single- and multiple-regressions techniques were used to measure other relationships between flaming duff reduction and independent variables. The best equation was a simple linear regression of flaming duff reduction on preburn duff depth. The relationship was very weak with an r^2 of 0.34. Additional data analysis will be needed before a final model can be developed for this portion of the research.

Table 10. Regression equations for flaming duff reduction (FDUFRED) based on flaming diameter reduction of the large, woody fuels (FDRED) for hardwood (HD) and Douglas-fir/hemlock (DF/H) units. All regressions are significant at the 95-percent level.

SPECIES	EQUATION	N[a]	r^{2b}	$s_{y.x}$[c]
				-Inches-
HD	FDUFRED = 0.368 + 0.066 SQRT(FDRED)	9	0.02	0.16
HD	FDUFRED = 0.219 + 0.093 DUFDEP	11	0.34	0.11
DF/H	FDUFRED = 0.186 + 0.314 SQRT(FDRED)	22	0.68	0.09

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

Sandberg (1980) showed that duff reduction in Douglas-fir and western hemlock underburns could be predicted from a simple thermodynamic equation based on the burning of woody fuels. This same theory was applied to the flaming consumption of the duff. Flaming duff consumption determined from several Douglas-fir and western hemlock prescribed burns has shown that a similar

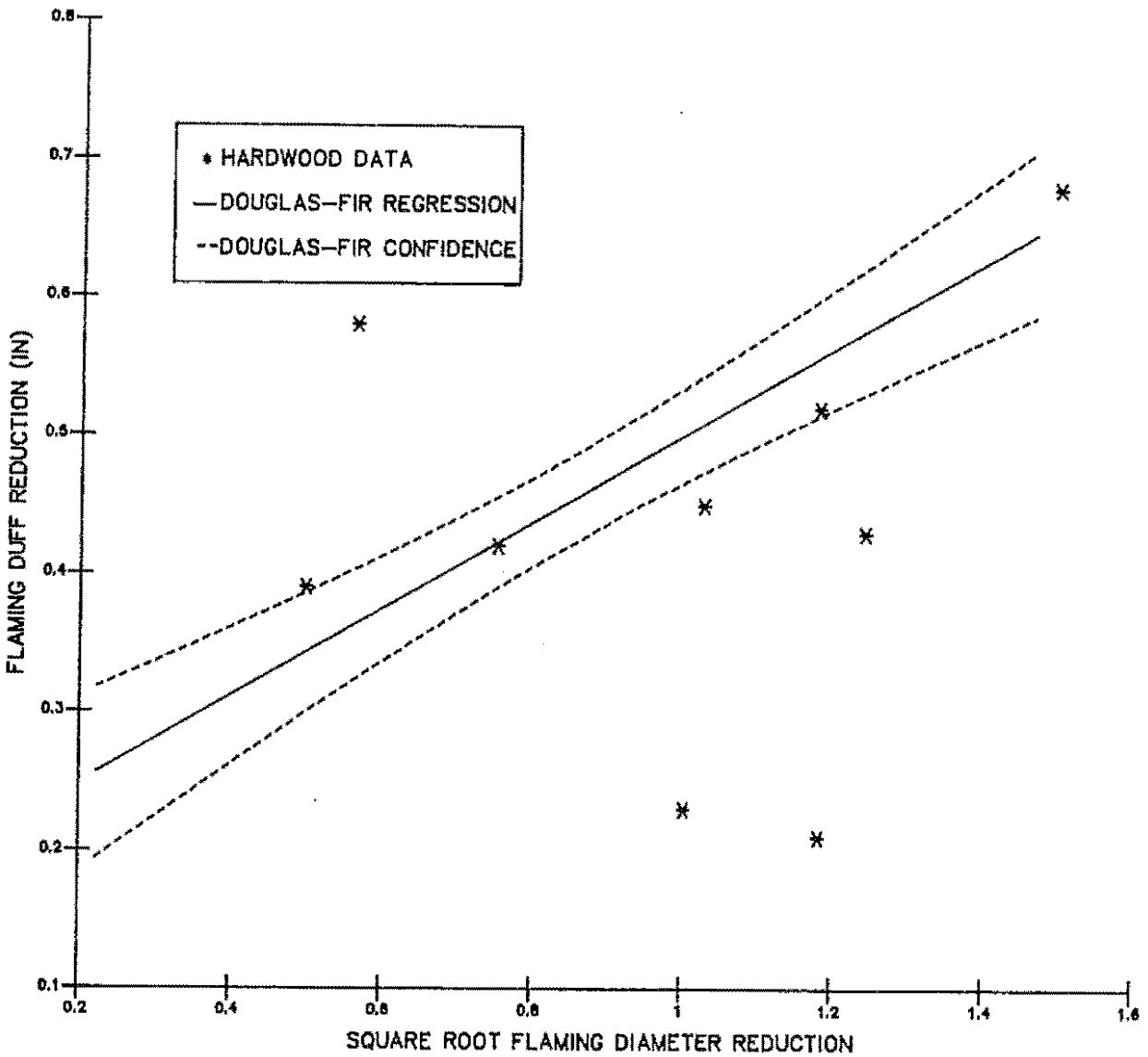


Figure 8. Flaming duff reduction plotted against large-fuel flaming diameter reduction for hardwood units. The solid regression line represents large-fuel flaming diameter reduction and duff reduction relationship established for Douglas-fir and western hemlock prescribed fires. Confidence bands are at the 95 percentile and are for the regression line.

relationship exists between woody fuels and duff consumption by combustion phase. For instance, flaming stage duff consumption can be estimated from the diameter reduction of woody fuels during flaming stage. A similar relationship was not shown to exist between the flaming duff consumption and woody fuel consumption with hardwoods.

6.2 Fuel Consumption Models-Eastside

6.2.1 Large, Woody, Fuel Consumption

Average diameter reductions for 14 of the 20 east-side units were regressed against several independent variables. Diameter reduction was best correlated with large-fuel moisture content (table 11).

Table 11. Regression equation for unit-average diameter reduction (DRED,inches) based on large-fuel moisture content (MEAS, percent) for east-side long-needled pine and mixed conifer (LNP/MC) units and Douglas-fir/western hemlock (DF/H) units. All regressions are at the 95-percent level.

SPECIES	EQUATION	N[a]	r^{2}[b]	$s_{y.x}$[c]
				-Inches-
LNP/AS	DRED = 5.38 - 0.103 MEAS	14	0.53	0.62
DF/H	DRED = 5.68 - 0.108 MEAS	21	0.86	0.34

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

An analysis of co-variance comparison test was performed on the east-side and westside linear regression equations to see if these regressions can be regarded as the same (Snedecor and Cochran, 1971). It was determined that there was a homogeneity of populations and no significant difference between slopes and y-intercepts of the two regression equations was noted. We therefore conclude that the westside woody fuel consumption equation developed for Douglas-fir and western hemlock can be used to represent east-side clearcut prescribed burns with uniform pine or mixed conifer slash and more than 1 inch of duff (figure 9).

Fuel consumption data from six of the 20 units were not used in the regression analysis. Three units did not have a homogeneous fuel bed and the burn was not continuous. One unit was burned very rapidly and a mass fire was obtained. It is hypothesized that under these extreme fire behavior situations, significantly less diameter reduction results.

Two units that were harvested in November were burned in March, very shortly after the snow melted. The average large-fuel moisture content was measured between 70 and 80 percent for both units. Large, woody fuels within the units were considered uncured. This is similar to the situation with the three hardwood units discussed earlier. We know that logs with this high of fuel moisture burn differently and we are currently involved in research to look at this situation. Preliminary results indicate there is a relationship between internal fuel moisture and diameter reduction for uncured slash units, although the slope of the regression equation is less steep.

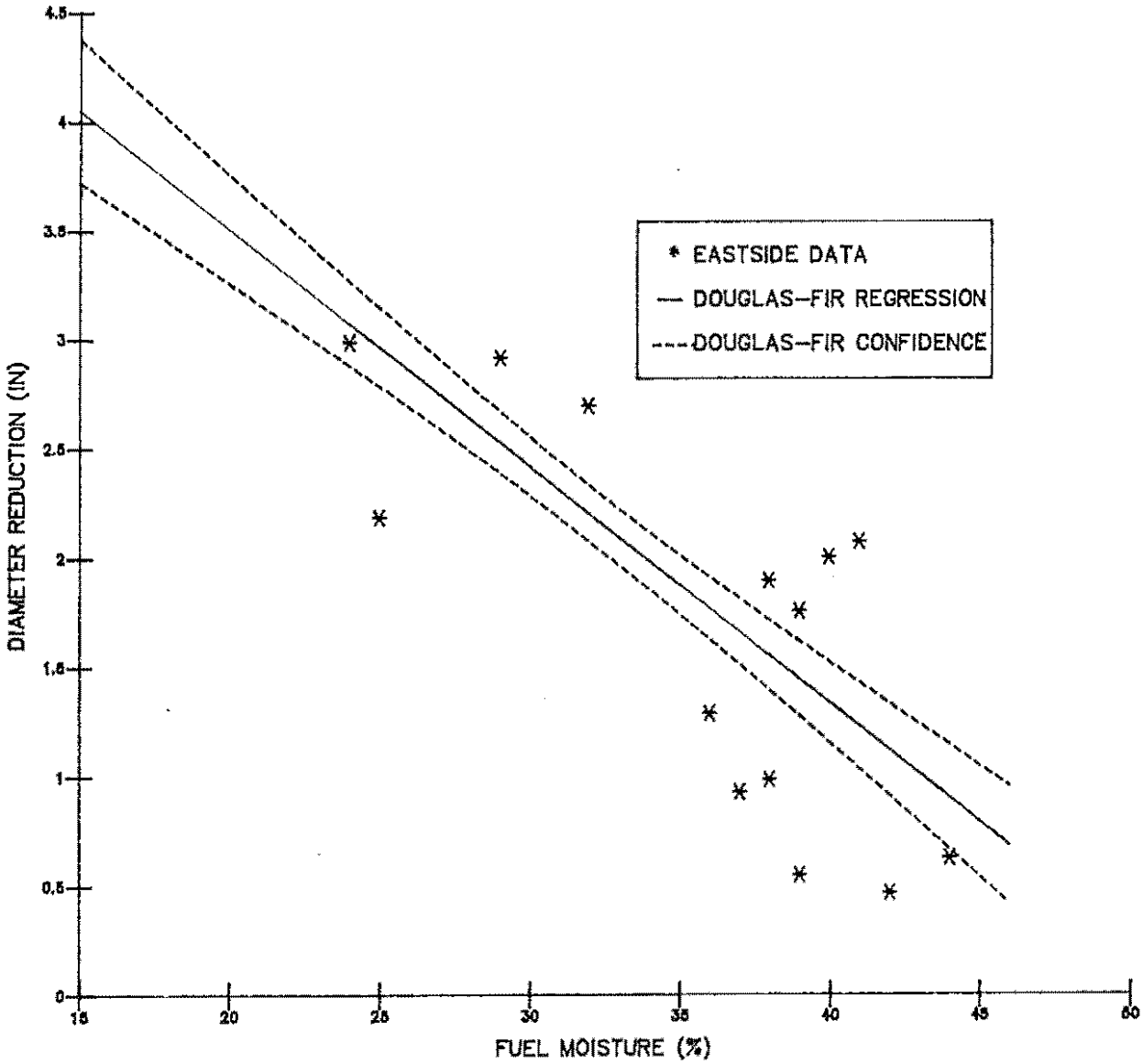


Figure 9. Large-fuel diameter reduction plotted against measured fuel moisture for east-side prescribed burns. The solid regression line represents the fuel moisture and fuel diameter reduction established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression line.

Fifteen of the 20 east-side units were measured for large-fuel diameter reduction during flaming stage. The proportion of large fuels consumed during the flaming stage were non-linearly related to consumption of the 1- to 3-inch diameter woody fuels (table 12). This is similar to the relationship found for Douglas-fir and western hemlock (figure 10).

Five units were ignited with a helicopter or obtained very high fire intensities and the flaming proportion approached 1.0. Under these conditions, the 1- to 3-inch consumption is no longer the single independent variable controlling flaming combustion.

Table 12. Regression equation for flaming proportion (FPROP) based on 1- to 3-inch woody fuel consumed (SMCON, tons/acre) for east-side long-needled pine and mixed conifer (LNP/MC) units and Douglas-fir/western hemlock (DF/H) units. All regression are significant at the 95-percent level.

SPECIES	EQUATION	N[a]	r^{2}[b]	$s_{y.x}$[c]
				-Inches-
LNP/AS	FPROP = 1 - EXP(-ABS(SMCON/5.346))**2.23	20	0.81	0.023
DF/H	FPROP 1 - EXP(-ABS(SMCON/4.626))**2.26	10	0.72	0.006

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

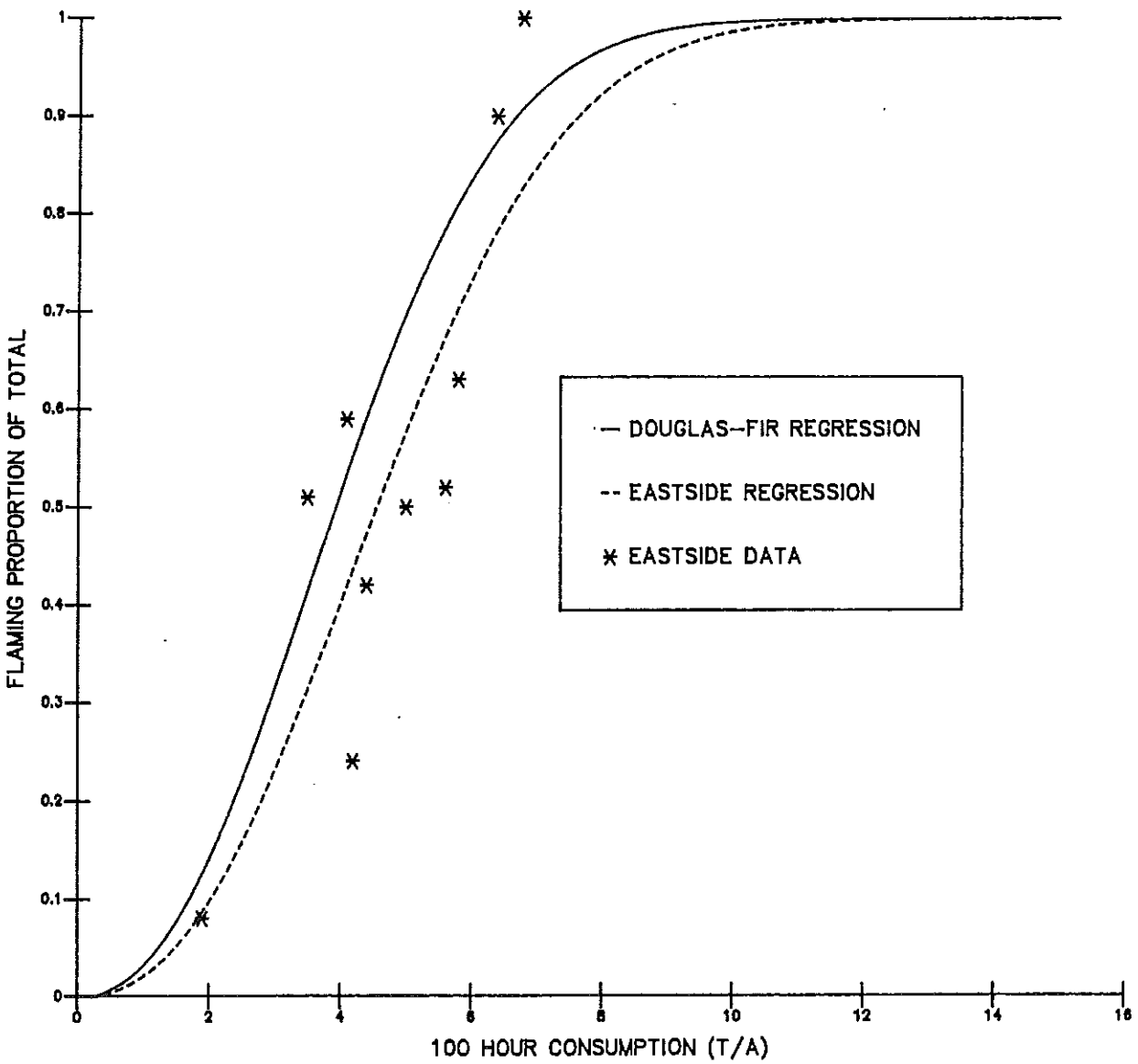


Figure 10. Flaming proportion of large-fuel consumption plotted against consumption of 1- to 3-inch diameter woody fuels for long-needled pine and mixed conifer prescribed burns on the eastside. Regression lines are displayed for east-side and Douglas-fir and western hemlock units.

6.2.2 Duff Consumption

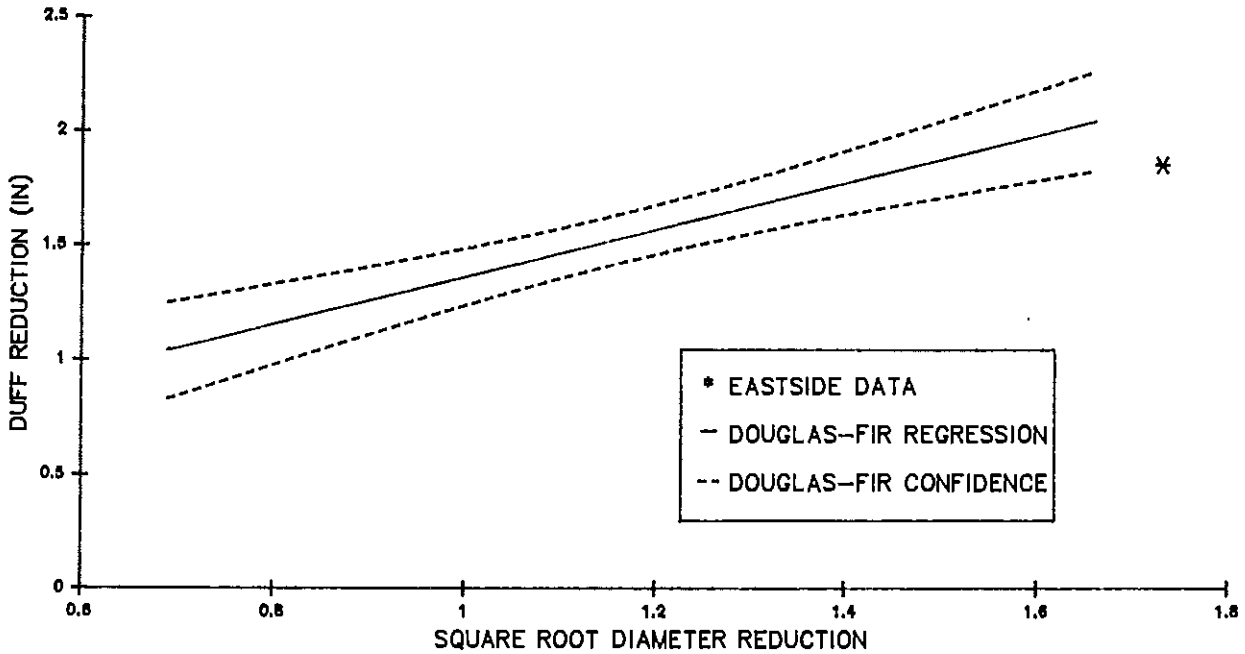
Results indicate that large fuel consumption is the controlling variable in determining the amount of duff consumed (table 13). However, when comparing east-side and Douglas-fir and western hemlock duff consumption regression lines, the slopes were significantly different (figure 11). The difference in slopes may be partly due to the shallow duff layer found on the east-side as compared to the westside. Additional data analysis for all prescribed burns monitored with shallow duff needs to be completed before a final duff consumption model is formulated. We believe this equation will be based on duff thickness.

One unit was categorized into a dry duff-moisture regime. Since only one unit fell into this regime, it is difficult to make any conclusive inferences (figure 11).

Table 13. Regression equations for unit-average duff reduction (DUFRED, inches) based on large-fuel consumption (LGCON, tons/acre) and large-fuel diameter reduction for east-side long-needled pine and mixed conifer (LNP/MC) and Douglas-fir and western hemlock (DF/H) units. All regressions are significant at the 95-percent level.

SPECIES	EQUATION	N[a]	r^{2b}	$s_{y.x}$[c]	Time since rain
				-(Inches)-	-(Days)-
LNP/AS	DUFRED = 0.656 + 0.024 LGCON	13	0.44	0.17	0-24
LNP/AS	DUFRED = --	1	--	--	25-60
DF/H	DUFRED = 0.515 + 0.058 LGCON	26	0.59	0.25	0-24
DF/H	DUFRED = 0.323 + 1.034 SQRT(DRED)	12	0.70	0.21	25-60

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.



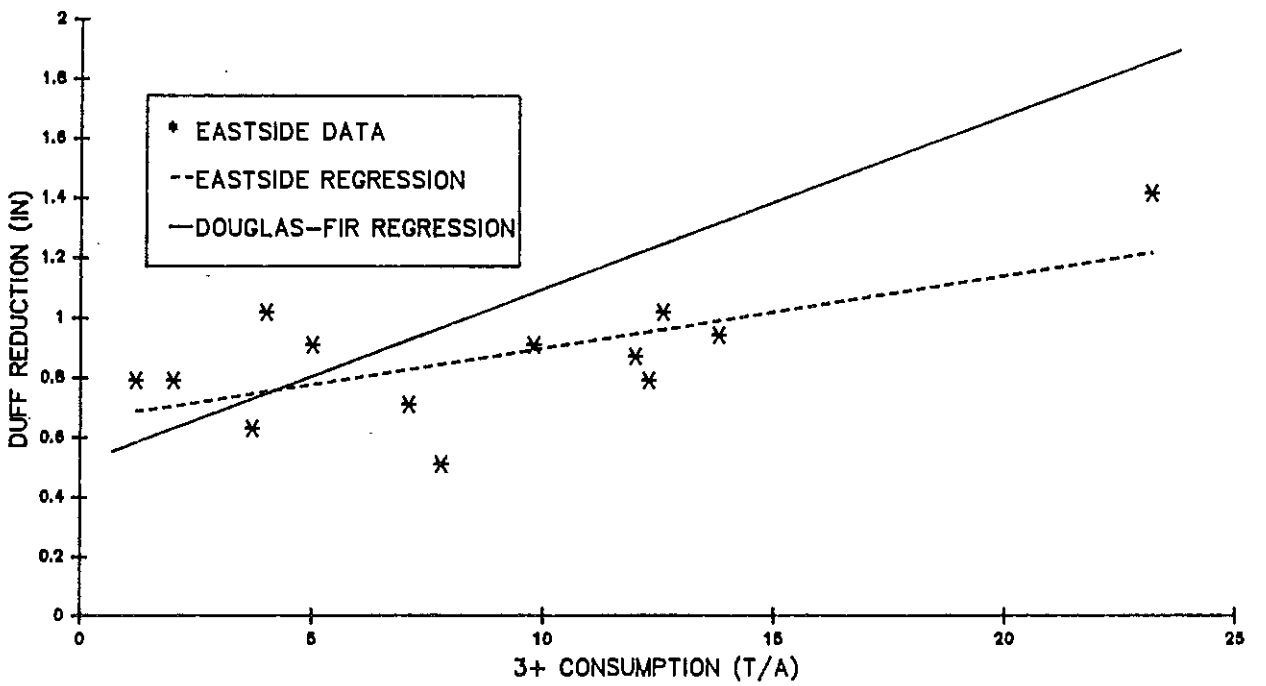


Figure 11. Duff reduction plotted against large fuel consumption for long-needled pine and mixed conifer units burned with less than 25 days since significant rain and greater than or equal to 25 days since significant rain. The solid regression line represents large fuel consumption and duff reduction relationship established for Douglas-fir and western hemlock prescribed burns. Confidence bands are at the 95 percentile and are for the regression lines.

Flaming duff reduction was regressed against the flaming diameter reduction of large woody fuels for long-needled pine and mixed conifer prescribed burns monitored on the eastside of the Cascade range (figure 12). A comparison between hardwood and Douglas-fir and western hemlock data indicate the variances are the same but the regressions lines have no common slope or common y-intercept (table 14). Consequently, the regression lines are significantly different.

Table 14. Regression equation for flaming duff reduction (FDUFRED) based on flaming diameter reduction of the large, woody, fuels (FDRED) for long-needled pine and mixed conifer (LNP/MC) and Douglas-fir/hemlock (DF/H) units. All regressions are significant at the 95-percent level.

SPECIES	EQUATION	N[a]	r^{2b}	$s_{y.x}$[c]
				-Inches-
HD	FDUFRED = -0.422 + 0.674 SQRT(FDRED)	10	0.81	0.111
DF/H	FDUFRED = 0.186 + 0.314 SQRT(FDRED)	22	0.68	0.090

[a]indicates the number of cases.
[b]indicates the coefficient of determination.
[c]indicates the standard error of the estimate.

6.3 Computer Model CONSUME

Results from this study have been incorporated into a fuel consumption program, called CONSUME. The updated version has been distributed to forest managers to assist in planning timber sale harvest specifications and to provide accurate data on fuel consumption for smoke management reporting.

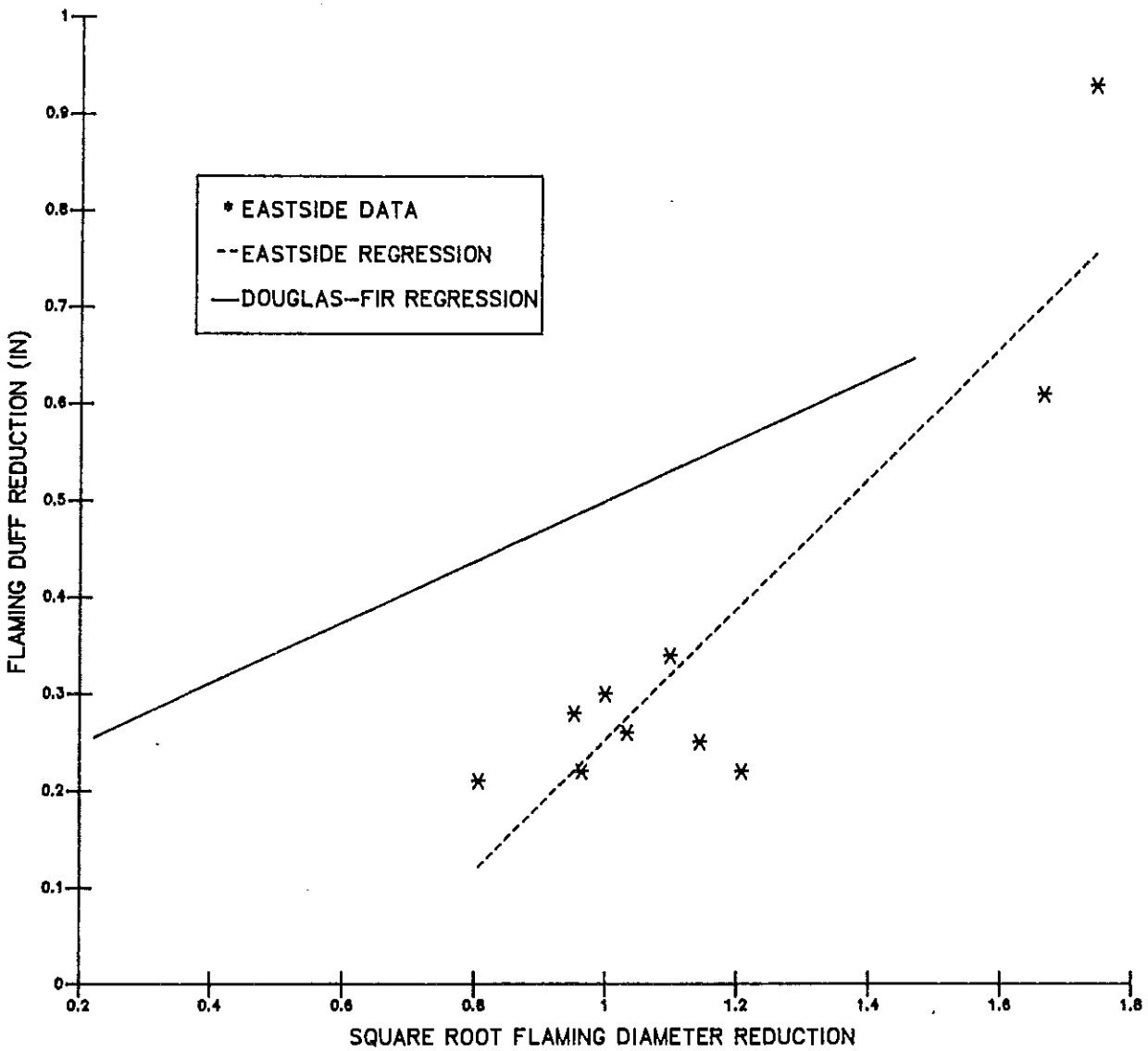


Figure 12. Flaming duff reduction plotted against large fuel flaming diameter reduction for long-needled pine and mixed conifer prescribed burns on the eastside. Regression lines are displayed for east-side and Douglas-fir and western hemlock units.

7.0 CONCLUSIONS

As a result of this study, we can quantitatively evaluate the opportunity to mitigate emissions produced from prescribed fire for hardwood, pine, and mixed conifer broadcast burn units. In addition, this study has provided an ability to evaluate emissions mitigation through inferences and quantitative estimates for slash piles and ponderosa pine prescribed fires (table 15). Forest managers and air quality managers will now be provided with the quanitative tools to plan effective utilization programs to effectively reduce air pollutant emissions.

The independant variables which best correlated with fuel consumption of hardwood and east-side fuel types were the same as the variables found to control the fuel consumption for Douglas-fir and western hemlock. Fuel moisture controlled the woody fuel consumption while total heat load and duration of heat controlled duff consumption. Although in some cases the relationship between the variables and the type of consumption were weak, they were the best relationships found from the analysis. The weak relationships are probably due to the considerable variation we had in burning conditions between units and the limited number of data points.

Table 15. Current knowledge of fuel consumption by cover and burn type and fuel-bed component for activity fuels. Highlighted numbers show an increase in knowledge level as a result of this interagency agreement. The level of burning activity for each cover-type component have been estimated.

Cover Type	Burn Type	Fuel Consumption By Fuel Bed Component				Burning Activity
		Live	Small	Large	Duff	
Douglas-fir/ Western hemlock	broadcast	4	1	1	1	H
	piled	-	4/2	4/2	4/2	H
West-coast hardwood	broadcast	4	3/1	3/1	3/1	H
	piled	-	4/3	4/3	4/3	L
Mixed conifer*	broadcast	4	3/1	3/1	3/1	H
	piled	-	4/3	4/3	4/3	H
Ponderosa pine	broadcast	4	3/1	3/1	3/1	H
	piled	-	4/3	4/3	4/3	H
Lodgepole	broadcast	4	3/1	3/1	3/1	H
	piled	-	4/3	4/3	4/3	H
Rocky mountain hardwood	broadcast	4	3	3	3	L
	piled	-	3	3	3	L
Juniper	broadcast	4	2	2	2	H
	piled	-	3	3	3	L
Redwood	broadcast	4	3	3	3	M
	piled	-	3	3	3	M
Chaparral	broadcast	4	3	-	-	L
	piled	-	-	-	-	L

1 -- Measured and/or modeled.
2 -- Sampled and/or inferred.
3 -- Know qualitatively.
4 -- No knowledge.

H - High
M - Medium
L - Low

* Mixed Conifer refer to mixture of species including western larch, Douglas-fir, grand fir, lodgepole pine, subalpine fir, and western white pine.

In most cases, analysis of covariate techniques indicated there were no significant difference between the hardwood and east-side algorithms compared with algorithms developed for westside Douglas-fir and western hemlock prescribed fires. Conclusions from this study include the following:

1. The relationship between woody fuel consumption and woody fuel moisture for hardwood slash and east-side slash appear to be similar to relationships already established for short-needled conifer species on the westside. Small fuels ignite larger fuels and the larger fuels will consume until quenched by internal fuel moisture.

2. Duff-reduction equations determined from this research for hardwood and pine indicate that combustion of duff usually occurs under the influence of burning woody fuels. When the duff is wet (days since rain less than 25 days), duff reduction was dependent on the total heat load supplied by combustion of large fuels. Under this wet duff moisture regime, duff will be dried to a depth that is dependent on large fuel consumption, and the duff will consume during smoldering stage to the depth at which it dried.

When the duff profile was dry (days since rain greater than or equal to 25 but less than 60), duff reduction was dependent on the duration of fire determined by diameter reduction of the large fuels. Under this drier condition, a dry layer is formed from meteorological processes which act as an insulating layer. The duration of heat, rather than total heat load, becomes the critical variable controlling the consumption.

Shallowness of the duff reduces consumption, possibly because of the higher mineral soil content within the duff layer. On several of the east-side mixed conifer and long-needled pine units, the duff was less than 2 inches in diameter. Under these conditions, woody fuel consumption determines duff consumption. However, the slope of the regression line is less steep than was found for Douglas-fir and western hemlock prescribed burns.

3. The proportion of large woody-fuel consumed during flaming stage was found to be controlled by the consumption of small (1- to 3-inch diameter) fuels. The small fuels ignited and consumed the large fuels until there were to few to interact. At this point, the large fuels would go into a smoldering stage and consume until quenched by internal fuel moisture.

Nonlinear regression equations developed from the hardwood and east-side prescribed burns were slightly different than equations developed from the Douglas-fir and western hemlock data set.

Flaming consumption of duff was thought to be dependent on flaming diameter reduction of large fuels. However, a clear case for this could not be statistically shown for the east-side units. Further analysis and possible data collection will be needed.

4. Utilization of logging residues in hardwood, east-side mixed conifer and long-needled pine fuelbeds is only slightly less effective than utilization of Douglas-fir and hemlock residues for reducing air pollutant emissions and preserving nutrient capital. Under like moisture conditions, similar woody-

fuel consumption occurs in each type. Removing residues reduces the duff layer consumed by fire, although not as dramatically as in westside fuelbeds.

8.0 APPLICATION OF RESULTS

The fuel consumption research presented in this report has resulted in a basic set of consumption models which are used extensively in smoke management reporting and prescribed burn planning. The results presented in this report have been utilized by a large clientel of land managers; air resource managers; air quality regulators; and atmospheric science and dispersion modeling research groups.

The fuel consumption models have been incorporated into a user-friendly computer program called CONSUME. Fuels management personnel in the states of Oregon, Washington, and California use the program daily in the preparation of environmental assessments and fire prescriptions for prescribed burning projects.. In addition, every prescribed burn must be preceded by a submittal of a smoke management report. The report must contain the projected amount of fuel to be consumed during the burning operation. This figure is used by the regulatory agency to evaluate if a prescribed fire will impact a designated air shed. The consumption figures reported by the managers are often derived from the CONSUME program or nomograms based on the fuel consumption equations from this report.

The fuel consumption equations are also used in an emissions inventory system developed for Oregon and Washington. The system estimates daily and annual emissions from prescribed burning. The inventory system is used to track emissions production over the years to determine if prescribed burning is complying with state regulations for emissions reduction.

Smoke dispersion modeling efforts utilize the fuel consumption equations to generate total particulate emissions and energy release for plume height. Improved dispersion models will require improved fuel consumption equations such as was developed from this study.

9.0 REFERENCES

Beaufait, W.R.; Hardy, C.E.; and Fischer, W.C. 1977. Broadcast burning in larch-fir clearcuts: the Miller Creek-Newman Ridge study. Res. Paper INT-175, Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment station, 73 p.

Brown, J.K. 1974. Handbook for inventorying down woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 24 p.

Brown, James K.; Marsden, Michael A.; Ryan, Kevin C.; and Reinhardt, Elizabeth D. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern rocky mountains. Res. Pap. INT-337. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 23 p.

Little, Susan N. 1982. Estimating the volume of wood in large piles of logging residues. Administrative Report PNW-1. Portland, OR: U.S. Department of agriculture, Forest service, Pacific Northwest Forest and Range Experiment Station. 7 p.

Little, Susan L.; Ottmar, Roger D.; and Ohmann, Janet L. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. Res. Pap. PNW-362. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 29 p.

Norusis, Marija J. 1988. SPSS/PC+ V2.0 base manual for the IBM PC/XT/AT and PS/2. SPSS Inc., Chicago, IL.

Ottmar, Roger D. 1986. Reducing smoke from prescribed fires: research solution to a management problem. In: Proceedings, annual meeting of the Northwest Forest Fire Council; 1986 November 18-19; Olympia, WA.

Ottmar, Roger D. 1987. Prescribed fire and fuel consumption in uncured slash--preliminary results. In: Proceedings, 9th AMS/SAF Conference on Fire and Forest Meteorology; 1987 April 21-24; San Diego, CA. Boston, MA: American Meteorological Society: 132-136.

Ottmar, R. D.; Little, S. N.; and Ohmann, J. 1985. Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. In: Proceedings, 8th AMS/SAF Conference on Fire and Forest Meteorology; 1985 April 29-May 3; Detroit, MI. Boston, MA: American Meteorological Society: 132-139.

Sandberg, David V. 1980. Duff reduction by prescribed underburning in Douglas-fir. Research Paper No. PNW-272. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 18 p.

Sandberg, D. V.; Ottmar, R. D. 1983. Slash burning and fuel consumption in the Douglas-fir subregion. In: Proceedings, 7th AMS/SAF Conference on Fire and Forest Meteorology; 1983 April 25-29; Fort Colins, CO. Boston, MA: American Meteorological Society: 90-93.

Sandberg, D. V. and Peterson, J. L. 1984. A source strength model for prescribed fires in coniferous logging slash. In: Proceedings, 21st Anual Meeting, Air Pollution Control association, Pacific Northwest International Section; 1984 November 12-14; Portland, OR.

Snedecor, George W.; Cochran, William G. 1971. Analysis of Covariance. In: Statistical Methods. Ames, IA: The Iowa State University Press: 419-446. Chapter 14.

10.0 GLOSSARY

CLEARCUT: A timber harvest method in which all, or nearly all, trees in a stand of timber are cut in one operation.

DIAMETER REDUCTION: Reduction in width of circular log caused by fire.

DUFF: Humus and other partially decayed material on the forest floor.

EASTSIDE: Geographic area in oregon or Washington east of the Cascade crest.

EMISSIONS: A release into the outdoor atmosphere of air contaminants.

FINE FUEL: Fuels that ignite readily and consume rapidly such as grasses, moss, and woody fuels between 0-1 inch in diameter.

FLAMING STAGE: That phase of the fire where fuel is ignited and consumed during flaming combustion.

FUEL LOADING: The amount of fuel present expressed quantitatively in terms of mass of fuel per unit area.

FUEL MOISTURE: The amount of water present in a fuel. Generally fuel moisture content is expressed as a precent of materials ovendry weight.

HARDWOOD: Tree species including red alder, tanoak, and vine maple.

LARGE FUEL: Fuels of large diameter (greater than 3 inches) such as logs and large limbwood.

LONG-NEEDLED PINE: Tree species including ponderosa pine, lodgepole pine and white pine.

MIXED CONIFER: Mixture of tree species including western larch, Douglas-fir, grand fir, lodgepole pine, subalpine fir, and western white pine.

PLANAR INTERSECT: A vertical sampling plane with no width along which all intersecting residue pieces are measured.

PRESCRIBED BURN: Controlled application of fire to wild land fuels in either their natural or modified state to obtain planned objectives of silviculture, wildlife habitat management, grazing, fire hazard reduction, etc.

SMALL FUEL: Fuels of small diameter (1-3 inch in diameter) such as small limbwood.

SMOLDERING STAGE: The combined processes of dehydration, pyrolisis, solid oxidation, and scattered flaming which occurs after the flaming phase of a fire.

WESTSIDE: Geographic area in Oregon or Washington west of the Cascade crest.

11.0 METRIC EQUIVALENTS

1 inch = 2.54 centimeters

1 foot = 30.48 centimeters

1 mile = 1.609 kilometers

1 acre = 2.47 hectare

1 ton = 0.907 metric ton

12.0 SCIENTIFIC AND COMMON NAMES OF TREE SPECIES

Douglas-fir	Pseudotsuga menziesii (Mirb.) Franco
Lodgepole pine	Pinus contorta Dougl. ex Loud
Ponderosa pine	Pinus ponderosa Dougl. ex Loud
Red Alder	Alnus rubra Bong.
Tanoak	Lithocarpus densiflorus (Hook. and Arn.) Rehd
True fir	Abies spp.
Vine maple	Acer circinatum Pursh
Western hemlock	Tsuga heterophylla (Raf.) Sarg.
Western red cedar	Thuja plicata Donn

MITIGATION OF PRESCRIBED FIRE ATMOSPHERIC POLLUTION THROUGH INCREASED UTILIZATION OF HARDWOODS, PILED RESIDUES, AND LONG-NEEDLED CONIFERS

FINAL REPORT

PART III--EMISSION CHARACTERIZATION

July 15, 1989

D.E. Ward, C.C. Hardy, D.V. Sandberg, and T.E. Reinhardt

IAG DE-AI179-85BP18509 (PNW-85-423)
Title: Environmental Impacts of Increased Residue/Slash Recovery

Submitted by:

USDA Forest Service
Pacific Northwest Research Station
Fire and Air Resource Management Project

ABSTRACT

Emissions from prescribed burning were characterized on twenty-three operational-scale tests in Oregon and Washington. The test areas were selected to represent fuel and fire types not previously studied, which included broadcast burning of clearcuts in three different fuel types (hardwoods, long-needled pine, and mixed-conifer) and pile burns of crane-piled slash and tractor-piled slash.

Components of the emissions measured were the primary combustion gases CO and CO_2, total particulate matter and particles smaller than 2.5 micrometers, trace gases, trace elements, and graphitic and organic carbon. Real time measurements of CO, CO_2, temperatures, and vertical velocities enabled the calculation of emission factors (mass of emission per mass of fuel consumed), rates of fuel consumption, source strength of emissions, and heat release rates. Derivation of the calculated parameters was based on the carbon-mass balance procedure. Models predicting fuel consumption rates were fit to data from twelve tests.

The observed and calculated variables from the 23 tests were compared with data from previous research in the Douglas-fir/hemlock (short-needled conifer) fuel type. Significant differences in emissions beween the piled tests and the broadcast burns were expected and observed. Heat release rates for the piled tests were a factor of 2-3 greater than for the broadcast burns. Emission factors for the broadcast burns were more similar between fuel types than expected. Emission factors for CO were similar for mixed conifer, long-needled pine, and hardwoods. The only difference in fine particulate emission factors was between long-needled pine and hardwood--the two least similar fuel types. Large variances in some of the variables diminished the strength of many of the correlations presented.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 BACKGROUND 3
2.1 Emissions Production 3
2.2 Fire Behavior 5
2.3 Smoke Production 6
2.4 Fuel Characteristics 9
2.5 Fuel Elemental Content 14
2.6 Emissions Elemental Content 15

3.0 OBJECTIVES 16

4.0 METHODS USED FOR MEASURING EMISSIONS 17
4.1 Test Area Selection and Fuel Complexes 17
4.1.1 Test Area Selection 17
4.1.2 Fuel Characterization 20
4.1.3 Unit-specific Fuel Descriptions 22
4.2 Description of Sampling Apparatus 23
4.2.1 Particulate Matter Sampling 27
4.2.2 Content of the Particulate Matter 29
4.2.3 Combustion Gases 29
4.2.4 Temperature of the Combustion Gases 31
4.2.5 Velocity of the Vertical Component 31
4.2.6 Data Acquisition and Control 32
4.2.7 Mechanical Support System 32
4.3 Calculated Parameters 33
4.3.1 Calculation of Emission Factors 34
4.3.2 Fuel Consumption 35
4.3.3 Rate of Energy Release 36
4.3.3.1 Carbon flux 36
4.3.3.2 Energy balance 37
4.3.4 Combustion Efficiency 37
4.3.5 Weighting of Emission Factors 38

5.0 RESULTS 40
5.1 Grab Samples 40
5.1.1 Primary Gases--Concentrations 40
5.1.2 Particulate Matter--Concentrations 41
5.1.3 Content of the PM2.5 42
5.1.3.1 Trace elements 44
5.1.3.2 Graphitic and organic carbon 44
5.2 Real Time Data 46
5.2.1 Temperature 46
5.2.2 Vertical Velocity 46
5.2.3 CO and CO2--Concentrations 48
5.3 Calculated Parameters 49
5.3.1 Emission Factors 49
5.3.1.1 Total particulate matter 51
5.3.1.2 Particles < 2.5 micrometers 52
5.3.1.3 Carbon dioxide 53
5.3.1.4 Carbon monoxide 54
5.3.1.5 Methane hydrocarbons 56

5.3.1.6 Nonmethane hydrocarbons 56
5.3.2 Rate of Fuel Consumption 56
5.3.2.1 Inventory methods 56
5.3.2.2 Carbon-flux method 58
5.3.2.3 Energy balance method 62
5.3.3 Rate of Energy Release 62

6.0 DISCUSSION 65
6.1 Homogeneity of Variances 65
6.2 Multiple Comparisons of Means 66
6.2.1 Differences Between Means--All Fuel Types 67
6.2.2 Differences Between Means--Broadcast Burns 68
6.2.3 Differences Between Means--Three Groups 69
6.3 Relations Between Combustion Products 69
6.3.1 Correlation(s) of Total Data Set 72
6.3.1.1 Concentrations of PM and PM2.5 72
6.3.1.2 CH4 and NMHC concentrations 72
6.3.1.3 EFPM and EFPM2.5 72
6.3.1.4 Combustion efficiency and EFCO 72
6.3.2 Correlations(s) Within Broadcast Burn Data 75
6.3.2.1 IR and total trace elements 76
6.3.2.2 IR and the sum of S, CL, and K 76
6.3.2.3 IR and elemental carbon 76
6.3.2.4 IR and EFPM2.5 76
6.3.2.5 IR and the EFPM-to-EFPM2.5 ratio 77
6.4 Modeling of Fuel Consumption 80
6.4.1 1984 Source Strength Model and What it Showed 80
6.4.2 New Efforts--Modeling By Parts 82
6.4.2.1 Smoldering phase 82
6.4.2.2 Flaming phase, first model 84
6.4.2.3 Flaming phase, second model 86
6.4.3 Summary of Models 89

7.0 APPLICATION OF RESULTS 90

8.0 REFERENCES 92

APPENDICES

Appendix A Concentrations by Fueltype
Appendix B Content of PM2.5
Appendix C Emission Factors, Carbon, Flux, I_R
Appendix D Rate of Fuel Consumption Plots
Appendix E Multiple Comparison of Means
Appendix F Correlation Matrices
Appendix G Modeled Fuel Consumption Plots

LIST OF FIGURES

Figure 4.1.2. Pre-burn stereo image of a photo point taken vertically from above a hardwood unit. 21

Figure 4.2.1. Configuration of the sampling array suspended above a pile (upper), and a clearcut (lower). 24

Figure 4.2.2. Schematic of the tubing and gas-train configuration used for real time measurements and "grab sampling" of emissions. 25

Figure 4.2.3. Schematic of analog-to-digital input/ output and electrical configuration for real time sampling system. 26

Figure 4.2.4. Flow chart of laboratory analyses performed on sampled gases and particles. 30

Figure 5.1.3. The content of the fine particles (PM2.5) for the six fuel types studied. Shown here are fire-averaged values for organic carbon, graphitic carbon, trace elements, and other compounds. 43

Figure 5.2.1. Real time measurements of vertical velocity and temperature, Cedar Pollard C (CPC) unit, package #3, plotted over time from ignition to extinction. 47

Figure 5.2.3. Real time measurements of carbon monoxide and carbon dioxide concentrations, Cedar Pollard C (CPC) unit, package #3, plotted over time for one hour following ignition. 48

Figure 5.2.4. Carbon dioxide and carbon monoxide account for over 95 percent of the total carbon released from the burning fuel. 49

Figure 5.3.1.1. Emission factors for PM (EFPM) illustrated for each fuel type by phase of combustion. 51

Figure 5.3.1.2. Emission factors for PM2.5 (EFPM2.5) illustrated for each fuel type by phase of combustion. 52

Figure 5.3.1.3. Emission factors for CO2 (EFCO2) illustrated for each fuel type by phase of combustion. 53

Figure 5.3.1.4.1. Emission factors for CO (EFCO) illustrated for each fuel type by phase of combustion. 54

Figure 5.3.1.4.2. Combustion efficiency illustrated for each fuel type by phase of combustion. 55

Figure 5.3.1.4.3. Plot of the strong relationship between combustion efficiency and EFCO. 55

Figure 5.3.2.2.1. Plot of the rate of fuel consumption for CC1--the test with the highest maximum rate. 59

Figure 5.3.2.2.2. The flaming versus smoldering portions of total fuel consumption for three categories of broadcast-burned fuel types --HW, LP, MC. 60

Figure 6.3.1.1 Linear association between concentrations of PM and PM2.5. The regression line is plotted with 95% confidence intervals. 73

Figure 6.3.1.2 Linear association between concentrations of CH4 and NMHC. The regression line is plotted with 95% confidence intervals. 74

Figure 6.3.1.3 Linear association between EFPM and EFPM2.5. The regression line is plotted with 95% confidence intervals. 74

Figure 6.3.1.4 Linear association between combustion efficiency and EFCO. The regression line is plotted with 95% confidence intervals. 75

Figure 6.3.2.1 Linear association between IR and the sum of all trace elements (as percent of PM2.5). The regression line is plotted with 95% confidence intervals. 77

Figure 6.3.2.2 Linear association between IR and the sum of the trace elements S, Cl, and K (as percent of PM2.5). The regression line is plotted with 95% confidence intervals. 78

Figure 6.3.2.3 Linear association between IR and elemental (graphitic) carbon (as percent of PM2.5). The regression line is plotted with 95% confidence intervals. 78

Figure 6.3.2.4 Linear association between IR and EFPM2.5. The regression line is plotted with 95% confidence intervals. 79

Figure 6.3.2.5 Linear association between IR and the difference between EFPM and EFPM2.5. The regression line is plotted with 95% confidence intervals. 79

Figure 6.4.2.1. The significant features of the smoldering phase model. 83

Figure 6.4.2.2. The significant features of the flaming phase--first model. 86

Figure 6.4.2.3. The significant features of the flaming phase--second model. 88

LIST OF TABLES

Table 2.3.1. Proximate analysis of selected species of hardwoods and softwoods (EKONO Inc. date unknown). 7

Table 2.3.2. Percent volatiles, fixed carbon, and ash for coal and different species of wood. 9

Table 2.3.3. Percent carbon content for typical forest fuels. 13

Table 4.1.1. Description of test units and fuel characteristics from recent research (1985 - 1987). 19

Table 4.2.1. Specifications for sensors, instruments, and control systems used in field sampling and laboratory analyses. 27

Table 5.1.1. Concentrations of gases for each phase of combustion, by fuel type. 41

Table 5.1.2. Concentrations of particulate matter (PM and PM2.5) for each phase of combustion, by fuel type. 42

Table 5.1.3a. Trace element and carbon content of the PM2.5 for each fuel type for the flaming phase. 44

Table 5.1.3b. Trace element and carbon content of the PM2.5 for each fuel type for the smoldering phase. 45

Table 5.1.3c. Trace element and carbon content of the PM2.5 for each fuel type for fire-averaged data. 45

Table 5.3.1. Emission factors for the primary emissions, for each fuel type, by phase of combustion. 50

Table 5.3.2.1. The field-inventoried (measured) fuel moistures and fuel consumption for each test. 57

Table 5.3.2.2. Fuel consumption determined for each test by three methods--inventory, carbon flux, and energy flux. Averages are also shown for each fuel type. 61

Table 5.3.3 Average, minimum, and maximum values of heat release rate (IR) for the six fuel types, by combustion phase. 63

Table 6.3.1 Linear regression equations for variables from the total data set and from only the broadcast burn data. 71

Table 6.4.2. Values for tf, Alpha, Beta, and maximum relative rate of fuel consumption for the models plotted in Appendix G. 89

1.0 INTRODUCTION

Open burning of biomass produces incompletely oxidized combustion products. These materials degrade air quality primarily by contributing to the background levels of gaseous and particulate matter pollutants. In the Pacific Northwest states of Oregon and Washington (PNW), planned forest fires produce about 100,000 tons of particulate matter annually. The production of emissions from open fires is affected by the various fuel, fire, and atmospheric variables. By performing preburn operations; i.e., fuel modification or careful fire prescription planning, the variables affecting pollution production can be used to advantage in reducing the quantity of pollutants produced. This report describes the characteristics of emissions contained with the smoke emitted from prescribed fires for various fuel and fire conditions. Differences in emissions production between fuel types and burning conditions were tested.

Emissions characterization of smoke from broadcast prescribed fires of logging slash from coniferous species in western Washington and western Oregon has progressed markedly over the past 10 years. Data are now available concerning emissions from burning of different forest fuels. Emissions from fires in many fuel types in the PNW have been characterized to assess the variances. The fuel types tested through this research include: hardwood logging slash, ponderosa pine-lodgepole pine, mixed conifer slash on the eastside of the Cascade Mountain Range, tractor-piled slash, crane-piled slash, and others.) Fire and air quality managers have incorporated these data in developing effective control strategies and in providing smoke management systems for the Pacific Northwest.

Emissions characterization research is extremely complex

because the measurement procedures require sampling of emissions using many different sensors operated simultaneously in a hostile environment. It is necessary to measure several of the variables at once to successfully measure any of the variables quantitatively. In addition to the large matrix of emissions variables requiring quantification, there is a need to quantify the fuel and fire behavior affecting the emissions produced. All of these factors dictate the use of a systematic approach to characterizing the matrix of variables.

2.0 BACKGROUND

2.1 Emissions Production

A final report prepared for the Pacific Northwest and Alaska Bioconversion Policy Group and Biomass Utilization Task Force (Ward and Hardy 1986) describes the techniques used and results for the types of emissions produced from broadcast burning of logging slash species dominated by Douglas-fir and hemlock. Their research examined the mass of particulate matter produced by two size classes: total particulate matter (PM) and particulate matter less than 2.5 micrometers mean mass cutpoint diameter (PM2.5), as functions of fuel and fire behavior variables. Also, the gases--carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and hydrocarbons other than methane (NMHC)--were quantified and these used to measure the fuel consumed in producing the emissions. This report describes follow-on work using the same sampling system for other fire and fuel combinations.

Ward and Hardy (1986) found emission factors for PM2.5 (An emission factor (EF) is defined as the mass of emission produced per unit mass of fuel consumed and is reported in units of g/kg or lbs./ton.) for the flaming combustion phase ($EF_{PM2.5}[F]$) to be as low as 33 percent of the EF_{PM} values for the flaming combustion phase period for the highest rates of heat release. $EF_{PM}[S1]$ and $EF_{PM2.5}[S1]$ values were found to be nearly equal for S1 conditions of moderately low heat release.[1]

---

[1]Throughout this report, a subscripting convention is followed whereby the variable being quantified is listed with a subscript for the emission variable followed in brackets by the phase of combustion that the value represents. If there are no brackets, then the value is assumed to apply for the entire fire.

In addition, $EF_{PM}[S2]$ and $EF_{PM2.5}[S2]$ are lower than $EF_{PM}[S1]$ and $EF_{PM2.5}[S1]$. These relationships are examined for other broadcast burns in other fuel types.

The abundance of the trace elements as a percent of the PM2.5 was investigated by Ward and Hardy (1986). They were hoping to find a specific element or combination of elements that would be produced proportional to the PM2.5. For example, the K-to-Fe ratio of 7 to 11 was long touted as being specific to smoke from forest fires and was used to apportion the contribution of smoke from prescribed fires to ambient air quality at receptor sites (Jenkins 1983). The error term associated with the quantification of the contribution of slash fire smoke at receptor sites is large (Core 1981). Ward and Hardy (1984) measured the K-to-Fe ratio for a large number of fires and found the ratio to be more variable than is acceptable with a coefficient of variation (CV) of 125 percent if the F and S phase emissions are examined. Other results showed that the total carbon was produced in a nearly constant ratio to the fine particulate matter (PM2.5). The development of a reliable set of characteristics useful as a tracer of forest fire smoke and for apportioning the contribution of smoke from forest fires at receptor sites is a goal of this research (Problem Area II of Research Work Unit Description for PNW-4401).

Other EF values have been quantified by Ward and Hardy (1986) for CO, CO_2, CH_4, NMHC, CH_3Cl, and a large number of polycyclic aromatic hydrocarbons (PAH) compounds including B[a]P. Results showed that CH_3Cl is not produced in a direct ratio to PM2.5 and that CH_3Cl is produced more abundantly during S1 and S2 than during F phase. B[a]P was shown to be produced more abundantly for those units with the highest consumption of living vegetation (brush). EF values for CO, CH_4, and NMHC were found to be lowest for the

F combustion phase and highest for the S2 combustion phase.

The technique for summing the carbon from each of the emissions and relating it back to the fuel consumed in producing the emissions is called the carbon mass-balance procedure (CMB). Methods used for CMB for grab and continuous samples and the quantification of the fuel consumption associated with each have been described by Ward (1981), Ward et al. (1982), Ward and Hardy (1984), and Ward and Hardy (1986). Nelson (1982) tested the CMB method under laboratory conditions and determined that the difference in fuel consumption using CMB and weight loss measurements using a load-cell weighing platform was less than 15 percent. Radke et al. (1986) successfully used CMB methods from airborne samples of emissions from prescribed fires. CMB methods have been used extensively and form the primary techniques of quantifying the fuel consumed relative to the emissons produced during the study.

2.2 Fire Behavior

Flaming (F), smoldering (S1 and S2), and glowing (G) combustion processes compete for available fuel and are markedly different combustion phenomena which contribute to the diversity of combustion products. The fuel characteristics (including arrangement, distribution by size classes, moisture, and chemistry) dominate in their affect on the emissions produced. The fire manager has basically three methods of altering the emissions produced: (1) Remove specific fuel elements from area to be burned, (2) prescribe acceptable fuel moisture content conditions, and (3) use preferred ignition techniques. These methods are often used in combination to achieve even greater emissions reduction.

F and G combustion are reasonably distinct combustion

processes that involve different chemical reactions and are physically distinct from a visual standpoint as well. F dominates during the startup phase with the fine fuels and surface materials supplying the volatile fuel gases required for the rapid oxidation reactions to be sustained in a F environment. The heat feedback from the flame structure and the diffusion and turbulent mixing of oxygen to the solid fuel interface contributes to the heat required to sustain the pyrolysis processes. During the initial periods of the F phase, the volatile hydrocarbons are vaporized from the fuels. Later, however, the decomposition of the cellulosic and lignostic cellulosic materials takes place through pyrolytic decomposition. These processes produce the fuel gasses which sustain the visible flaming processes.

Once carbon begins to buildup on the solid fuel surfaces, then the pyrolytic reactions no longer produce sufficient fuel gases to maintain the flame envelope. It then becomes essential that oxygen diffuse to the surface which is enhanced through turbulence in the combustion zone and through premixing by introducing the oxygen at ground level. This allows surface oxidation to take place at the solid fuel surface and provides for heat evolution and heat feedback to accelerate the pyrolytic reactions and volatilization of the fuel gases from the solid fuel. The process ultimately leads to the production of charcoal where the only combustion occurring is of the glowing type--or surface reaction of oxygen with carbon.

2.3 Smoke Production

An examination of data concerning different species of hardwoods and softwoods confirms some of our earlier findings of smoke production from units of broadcast burning of hardwood slash. Preliminary data show emission factor values for both PM and PM2.5 to be similar for conifer and

hardwood species. EKONO Inc. (date unknown) in a survey of various species of firewood for residential heating, show heavy smoke production from southern pines and Douglas fir, medium smoke production from the less dense hardwood species and all the other softwoods, and virtually no smoke from high density hardwoods. Typical analyses of C, H_2, S, O_2, N_2, and ash show carbon contents for softwood species ranging from 49 to 59 percent with hardwoods from 49 to 52 percent (table 2.3.1). Oxygen content ranges from 33 to 45 percent for softwoods and from 41 to 45 percent for hardwoods. The range for ash content is similar for softwoods (0.2 to 2.2 percent) and hardwoods (0.15 to 1.35 percent).

Table 2.3.1. Proximate analysis of selected species of hardwoods and softwoods (EKONO Inc. date unknown).

Chemical Species	Coal	Douglas-Fir	Poplar
C	76.3	52.3	51.6
H_2	4.8	6.3	6.3
O_2	4.0	40.5	41.5
N_2	0.6	0.1	---
S	1.2	---	---
Ash	9.7	0.8	0.65
Moisture	3.4	---	---

For the combustion of hydrocarbons, there is a balance between thermal decomposition and hydroxylation. The hydrocarbon molecules are first attacked by the oxygen free-radical producing an unstable hydroxylated compound which in turn forms an aldehyde compound. The aldehydes break down to formaldehyde which may further be oxidized to either CO and H_2O or CO_2 and H_2O. If the conditions favor hydroxylation (such as preheating the hydrocarbons and air, and allowing time for the attachment of oxygen atoms on the hydrocarbon molecule), there will be little or no soot formed. If, however, conditions favor cracking, as, for example if the hydrocarbons and oxygen from the air are not thoroughly mixed together, the heat from the combustion of part of the hydrocarbon molecule cracks the hydrocarbon molecule and soot is formed. Hence, if conditions favor "cracking," the hydrocarbon will decompose thermally into carbon and hydrogen, and will burn with a smokey flame.

Significant differences exist for the percent weight of material that will boil off as volatiles and the percentages of fixed carbon, water, and ash as is illustrated in table 2.3.2. It is apparent from data in table 2.3.2 that the percent volatilizable is a function of the moisture content of the fuel and that the fixed carbon is greater for higher moisture content fuels. The temperature of the solid fuels are significantly different as well as the combustion zone temperature. These are a function of fuel moisture content.

Table 2.3.2. Percent volatiles, fixed carbon, and ash for coal and different species of wood.

Type of fuel	Moisture Content	Volatile Material	Fixed Carbon	Ash
	(percent)			
Bituminous coal	2.5	37.6	52.9	7.0
Hardwood (wet)	45.6	48.6	5.5	0.3
Hardwood (dry)	0.0	89.3	10.1	0.6
Southern pine (wet)	53.3	31.5	15.9	0.3
Southern pine (dry)	0.0	66.0	33.4	0.6

Various factors contribute to the temperature in the flame zone. The flame zone temperature affects the production and character of the smoke produced by the fire. For example, excess air can reduce the flame temperature as can high moisture content fuels. Lower flame temperatures will promote the production of particulate matter and other partially oxidized combustion products, so that as the moisture content of the fuel increases, the temperature decreases and the hydrocarbon gases volatilized from the solid fuel become diluted which reduces the rate of the oxidation reactions and lowers the flame temperature. Similar factors dominate in the formation of graphitic carbon. For higher temperature fires the molecules of the fuel are essentially stripped of hydrogen and oxygen atoms leaving the carbon to condense if adequate oxygen is not present to complete the oxidation process.

2.4 Fuel Characteristics

Each type of fuel is unique in chemical composition, size, shape, moistue, arrangement, etc. These unique fuel elements are distributed in semi-random fashion across burn

areas. Involvement of the fuel elements in the combustion process is interdependent on the association of fuel elements. Thus, fuel elements of like characteristics may not burn under the same combustion conditions just because of the interdependence of fuel elements. This affects the production of emissions, but in unknown proportions.

Individual fuel elements will contribute differently to the total combustion process--both the flaming and smoldering phases. Forest fuels differ in the amounts of extractives, nitrogen, proportion of lignin and cellulose, etc. Some of the prominent forest fuels of interest for this work are conifer and hardwood litter duff, sound woody fuels, rotten woody fuels, and the brush, grass, ferns, and sprouts from hardwood species.

Brown (1972) reported on the fuels supporting the flaming front of experimental fires in prepared fuel beds. Fires were extinguished with water after the rear of the propagating flame front had passed. He found that fuels of less than 1 cm. diameter accounted for half of the total weight loss even though this size material comprized less than 30 percent of the total loading. Fuel greater than 3 cm. in diameter provided only about 10 percent of the total weight loss in the flame front. No change in diameter was observed for particles of this size. Hence, very little reduction in the larger fuels and/or duff fuels would be expected accompanying the main flame front passage. There is a need to measure fuel consumption using nondestructive sampling methods (Ward and Hardy 1986).

Large, woody fuels (greater than 3 inches in diameter) and duff comprise the major proportion of fuels consumed by fire. During the flaming period, the smaller fuels (less than 3 inches in diameter) sustain consumption of the large surface fuels. The smoldering stage follows, until quenched

by the internal fuel moisture of a log (Sandberg and Ottmar 1983; Ottmar 1983).

The organic duff layer is initially ignited by the woody fuels and dried to a depth determined by the duff moisture and heat output of the surface fuels. The duff will then smolder to this dried-out depth (Ottmar and others 1985). Only if the moisture content of the duff is less than 30 percent will the duff burn independently of woody fuel consumption (Sandberg 1980). It is likely that duff is one of the major sources of air pollutants. This is especially true for conditions that promote duff consumption.

Duff fuels serve as a nutrient reservoir. It was reported that in nine old-growth stands in western Washington the duff contained 70 tons of organic matter and 1800 pounds of nitrogen per acre. Nitrogen is often a limiting factor in the growth of Douglas-fir in the Pacific Northwest; hence, the loss, accumulation, and cycling of this element in and between vegetation, forest floor, and soil are particularly significant. The nitrogen can be volatilized during the combustion of the duff either as elemental nitrogen or as various different nitrogenous gases; i.e., NO, NO_2, NH_4, N_2O. NH_3, NO_3, and others. These emissions pollute the atmosphere and deplete the nitrogen reserves. The fuel elemental content is discussed in more detail in section 2.5.

Duff fuels contribute significant quantities of particulate matter when smoldering combustion is allowed to persist over prolonged periods of time. The particulate matter emission rate is high, but the heat release rate is low; which translates into high concentrations of particulate matter at or near the surface. For example, Pickford et al. (1976) found EF_{PM} values for lifted beds of forest floor duff fuels for Douglas fir/hemlock burned at the University of

Washington combustion hood facility to range from 8.9 to 97.7 g/kg. The flaming combustion EF_{PM} were consistently lower than the smoldering EF_{PM} values. Smoldering EF_{PM} values were highest immediately following flameout and then decreased over the smoldering period. Final EF_{PM} values were often 50 percent or less of the EF_{PM} values immediately following flameout. Ward and Hardy (1986) verified these findings using field sampling techniques. This research will investigate the time-derivative production of emissions from the flaming and smoldering combustion phases for other fuel types.

Knowledge concerning the fuel carbon elemental content continues to be important in using the CMB technique for assessing fuel consumption. The need for measuring carbon content of the fuels burned is dependent on the variation in carbon content of the fuels. Generally, the typical forest fuel contains about 50 percent carbon and has a generalized molecular formula of $C_6H_9O_4$ (Byram 1954). Several researchers have reported, for different fuels, carbon contents somewhat different than 50 percent as shown in table 2.3.3. It is not clear, in some cases, if the percent carbon analyses have been corrected for mineral and/or moisture contents of the fuel samples. This can make a large difference, and values as low as 26% carbon would not be expected.[2]

[2]Personal communication, Dr. Ronald Susott, USDA Forest Service, Intermountain Fire Sciences Laboratory, Missoula, Montana, 1989.

Table 2.3.3. Percent carbon content for typical forest fuels.

Fuel component	Percent carbon	References
Douglas-fir wood	50	Edmonds et al.(1980)
Douglas-fir bark	53.3	"
Alder wood	49.8	"
Alder bar	51.1	"
Douglas fir sapwood	49	Bollen (1974)
" heartwood	51	"
" bark	54	"
" needles	56	"
Alder litter layer	51	"
Alder F layer	40	"
Conifer L layer	42	"
Conifer F layer	26	"

Although, percent carbon of the fuel may change with time during the combustion process, this has not been found to be the case and has never been believed to produce a source of error greater than ± 10 percent. Comery (1981) showed, for litter under a longleaf pine stand, that carbon enrichment is insignificant and deviates from 50 percent by less than ± 5 percent.

2.5 Fuel Elemental Content

Grier (1975) compared nutrient content on sites before and after an intense wildfire and postulated that nutrient losses by volatilization and ash transport amounted to 907 kg/ha for nitrogen; 75 kg/ha for calcium; 33 kg/ha for magnesium; 308 kg/ha for potassium; and 698 kg/ha for sodium. Culver and Pickford (1980) undertook a research study to determine the atmospheric losses of nutrients from burning ponderosa pine litter. They found significant losses of nutrients and that nutrient losses were greater for simulated head fires than for backfires. A major weakness was their inability to effectively separate particles by size class prior to nutrient analyses.

The composition of trace element content of particulate matter is of considerable interest because these materials, if produced in a uniform ratio with the particulate matter, could conceivably serve as a tracer in the atmosphere for differentiating particulate matter from prescribed fires from that produced from other sources. A potentially deleterious consequence of prescribed burning is the depletion of trace elements from the site and transport of these materials away from frequently burned areas. It could take years to replace the nutrients lost from sites if these losses are significant.

Culver and Pickford (1980) found contradictory results regarding the loss of calcium, potassium, and phosphorous from fuelbeds of ponderosa pine litter burned under a combustion hood. In general, they found losses of the trace elements from the fuelbed exceeded the trace element contained with the particulate matter for calcium and potassium but not for phosphorous. For phosphorous, approximately two times the amount of phosphorous was found with the particulate matter as was measured from the

fuelbed. No explanation for the discrepancy was presented. It conceivably could have resulted from contamination of the filter sampling medium or other contaminants introduced during sample analyses.

2.6 Emissions Elemental Content

The variance of production of trace elements with PM and PM2.5 is poorly understood for the range of species and burning conditions of fires in the Pacific Northwest. It has been shown that different trace materials are produced as functions of fire behavior related variables (e.g., K/Fe is a function of combustion efficiency; K, Cl, and S are functions of the rates of heat release from the fire; CH_3Cl decreases with increasing rates of heat release whereas the Cl content of the PM2.5 increases with increasing heat release rates; and the Na content of the PM2.5 decreases with increasing temperature in the sampling zone. All of these variances contribute to the uncertainty of identifying a single element or ratio of elements that can be used for apportioning the particulate matter from prescribed fires against other sources. More detail is required concerning the effect regional variances and/or fuel variances have on the production of the trace elements. The present report includes data from tests in new fuel and fire situations that have enhanced the identification of the variances of these trace materials as functions of fire and fuel variables.

3.0 OBJECTIVES

The objectives for the research are as follows:

3.1 To measure emission factors for PM, PM2.5, CO, CO_2, CH_4, NMHC, B[a]P, and other POM compounds, a variety of trace gases (CH_3Cl, NO_2, COS, and others), and trace elements for at least three periods of time during the course of each fire to include flaming (F), first smoldering (S1), and second smoldering (S2) combustion periods.

3.2 To measure the rate of fuel consumption and emissions source strength over time for flaming and smoldering combustion phases as a function of fuel conditions.

3.3 To fit equations to the rate of fuel consumption and subsequent rate of emissions production over the duration of the fire.

3.4 To identify the rate of decay of the emissions as a function of time, fire, and fuel variables.

3.5 To compare these measurements and models with those already developed for broadcast burning of coniferous species logging slash in western Washington and western Oregon.

4.0 METHODS USED FOR MEASURING EMISSIONS

The methods used during this study are similar to those described by a previous study plan (Ward 1981) and by Ward and Hardy (1984, 1986). The previous work included tests on twelve broadcast burns of clearcut Douglas-fir and hemlock. To summarize the present study, test areas were located on a variety of hardwood sites in Washington and Oregon where units are being converted from hardwood species such as maple and/or alder to conifer species. Other test units were located east of the Cascade mountain range on clearcut units of ponderosa and/or lodgepole pine and on units of mixed-conifer species. Tests were also done on piled slash in western Washington. Tower and cable systems were used to support sampling equipment over the fires. Both continuous and grab sampling were done from the same sample packages and included samples of the gases and particulate matter. A number of new protocols were introduced including the use of a traversing system for sampling emissions from fires in piled slash and new fuel sampling strategies. These will be described in more detail in the following sections.

4.1 Test Area Selection and Fuel Complexes

4.1.1 Test Area Selection

Twenty-three individual tests were performed at eleven sites selected from logging units in Washington and Oregon that would represent the range of fuel and fire conditions found in the Pacific Northwest. Sites selected for this research were found in the five distinct fuel complexes described below (unit-specific details are given in table 4.1.1):

1. Hardwood (8 tests)--Broadcast-burned units with logging slash that is predominantly of hardwood species (such as big-leaf maple, vine maple, and red alder). Hardwood slash is created primarily by the harvest/conversion of units from alder to coniferous

species. These units are found almost exclusively on the west slopes of the coast range (coastal Oregon and Washington. Prescribed burning of hardwood units begins as early as February, and extends into late September and October. Because units with this fuel type are located along the western coast, much of the burning is done in mid-summer (July/August) when transport winds are favorable.

2. Pine (4 tests)--Broadcast burns of logging slash in long-needled pine (ponderosa pine, lodgepole pine) found in Washington and Oregon east of the Cascade Range. Long-needled pine slash is found in lower elevation units (<2500' msl). The burning season begins in early spring immediately after snow-melt, and extends to mid-June. Late fall (Sept-Oct) burning in pine is less typical.

3. Mixed conifer (3 tests)--Broadcast underburns in slash comprised of long-needled pine mixed with associated species (the true firs, Engelmann spruce, western larch) found in Washington and Oregon east of the Cascade Range. Mixed conifer slash is found in higher elevation units on the east slopes of the Cascade Range, and on mountain ranges such as the Blue in Oregon and the Selkirks in Washington. Burning is done in late spring after snow-melt, and again in the fall from late September through October.

4. Tractor/dozer-piled (4 tests)--Coniferous species slash (Douglas-fir, hemlock, western red cedar) in western Washington and Oregon is piled by bulldozer and then burned. Slash is piled on landings wherever logging is performed, but the piles are often burned in late fall or winter. Slash in eastern Oregon and Washington is often piled throughout the entire unit, where access and soil conditions permit--particularly in long-needled pine. The piles are burned in late fall and winter.

5. Crane-piled (4 tests)--Crane-piled slash is logging debris (primarily woody) on landings where cable-yarding methods are used to gather logs, and is found on units of the coast range of western Washington and Oregon, along the east side of the Olympic Mountain Range, and along both sides of the Cascade Mountain Range. The unmerchantable material is stacked by a loader or crane, and is burned in late fall and winter or with the unit where broadcast burning is performed.

A sixth major fuel complex commonly broadcast burned in the Pacific Northwest is logging slash from coniferous species

(Douglas-fir, hemlock, western red cedar) in western Washington and Oregon. This fuel complex is perhaps the most predominant in the Pacific Northwest, and it is found on lower elevation sites throughout the region east of the Cascade Mountain Range. Emissions research has been previously described for twelve tests in this complex (Ward and Hardy 1986) and has been the basis for the present study. Data from these twelve tests--labeled "DF" to represent Douglas-fir/hemlock-- are included in this report.

Table 4.1.1. Description of test units and fuel characteristics from recent research (1985 - 1987).

Test name	Fuel complex	Date burned	Test location	Pre-burn fuel loading		
				Woody	Duff	Total
				- - - - (Kg/m2) - - - -		
GHA	HW	07/15/85	Hebo, OR.	4.2	22.1	26.3
EAA	HW	07/18/85	Hebo, OR.	4.1	8.9	13.0
VIC	HW	09/25/85	Arlington, WA.	4.8	3.8	8.6
CPC	HW	06/12/86	Hebo, OR.	7.0	12.2	19.2
LB1	HW	09/05/86	Hebo. OR	6.6	9.1	15.7
LB2	HW	10/10/86	Hebo, OR.	6.1	3.5	9.6
LB3	HW	09/04/86	Hebo, OR.	7.3	4.8	12.1
LB4	HW	09/03/86	Hebo, OR.	7.5	6.9	14.4
LL1	LP	05/22/86	Bend, OR.	4.4	0.0	4.4
LL2	LP	06/04/86	Bend, OR.	3.8	0.0	3.8
CC1	LP	10/02/86	Leavenworth,WA	4.8	0.0	4.8
CC2	LP	10/05/86	Leavenworth,WA	5.5	0.0	5.5
RSP	MC	06/26/87	LaGrande, OR.	6.3	3.3	9.6
WHH	MC	06/29/87	LaGrande, OR.	9.2	6.4	15.7
HESS	MC	07/01/87	LaGrande, OR.	6.6	4.3	10.9
				- - - (Total Kg) - - -		
PIL1	TP	02/13/86	Arlington, WA.	2358.7	N/A	2358.7
PIL2	TP	05/15/86	Arlington, WA.	2358.7	N/A	2358.7
PIL3	TP	07/24/86	Arlington, WA	3810.2	N/A	3810.2
PIL4	TP	08/02/86	Arlington, WA.	5080.3	N/A	5080.3
SKY1	CP	05/26/87	Skykomish, WA.	1723.7	N/A	1723.7
SKY2	CP	05/26/87	Skykomish, WA.	2993.7	N/A	2993.7
SKY3	CP	05/27/87	Skykomish, WA.	2086.5	N/A	1995.8
SKY4	CP	05/28/87	Skykomish, WA.	2268.0	N/A	2268.0

Several criteria were used in selecting the 15 broadcast burn study units from over 50 candidates visited: (1) Physical constraints imposed by the sampling method included a maximum limitation on slope of 20 percent, and vehicle access was required to within 100 feet of the area to be sampled; (2) Health and safety concerns required careful consideration of fireline protection and proximity to extreme heat and smoke; (3) Fuelbed characteristics were evaluated with respect to loading (mass per unit area), arrangement, continuity, species distribution of woody debris, time since harvest, and relative abundance of live vegetation. Units from each fuel type/arrangement were selected to represent a range of typical fuelbed scenarios experienced in operational management activities.

4.1.2 Fuel Characterization

The fuels on each of the broadcast burns were characterized with respect to both the pre-burn and post-burn mass of woody and duff material. The planar-intersect method of downed woody fuel inventory (Brown 1976) was used in each test area with a grid of transect lines established for repeatable pre-burn vs. post-burn measurements. By utilizing Ottmar's technique for measuring the consumption of large woody fuel and duff, fuel consumption was determined for each phase of consumption as well as for the entire fire. In addition, a unit-averaged moisture content was gravimetrically determined for woody material larger than 3 inches (1000-hour fuel moisture) using cross-section samples from at least forty logs on each test. This data as well as total fuel consumption and woody fuel moisture is presented in table 4.1.1 for each unit.

The mass of each dozer-built pile was estimated by making pile area and volume measurements and reducing the data to oven-dry mass using species-dependent density/mass tables.

The crane-built piles were weighed during construction on portable truck scales, and the oven-dry mass was determined using the weight data and moisture measurements taken randomly throughout each pile.

Stereo-paired photographs were taken of the fuels before and after each test for subsequent photogrammetric evaluations of changes in the fuelbed(s). Two fixed-base cameras were suspended from the tower-and-cable support equipment (used for emissions sampling) and were positioned over pre-established photo points before and after each test. The photographs provided stereo images of each photo point for both qualitative and quantitative analyses of pre- and post-burn fuel and vegetative structures. The stereo images were used for quantifying live vegetation abundance on the broadcast burn tests and were used to determine fuel volume on the piled-slash tests. The pre-burn stereo image of a photo point from a hardwood unit are seen in figure 4.1.2.

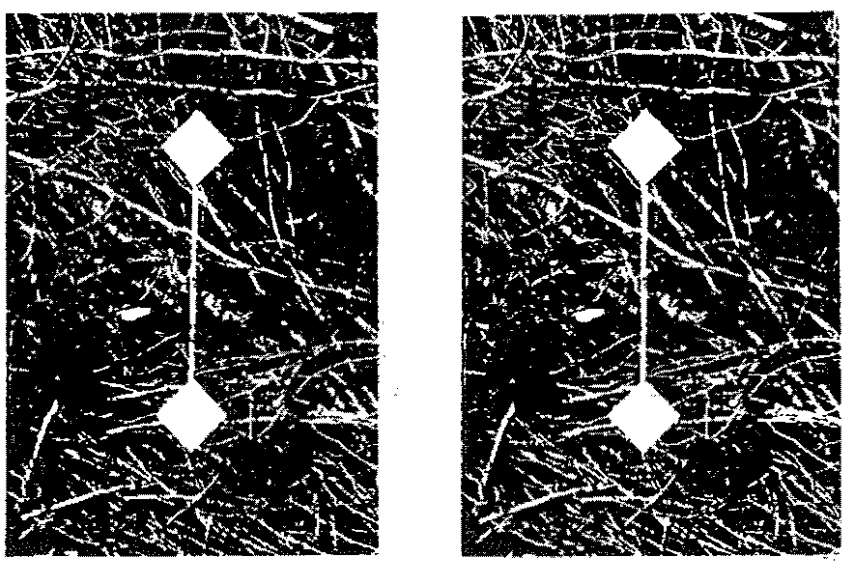


Figure 4.1.2. Pre-burn stereo image of a photo point taken vertically from above a hardwood unit.

4.1.3 Unit-specific Fuel Descriptions

The fueltype and/or arrangement for each individual test unit is described below. (Details regarding measured fuel parameters for the individual units are given previously in table 4.1.1):

1. Hardwood units ("HW"). Two units--GHA and EAA--had similar woody fuel species and loadings, but woody debris on GHA had cured, while on EAA the woody fuel still contained live fuel moisture due to the limited time since harvest. In addition, the duff loading on GHA was double that of EAA--the GHA unit had the most duff of all the hardwood units selected. The VIC unit was nearly 200 miles north of the other eight hardwood units, and was selected for geographical diversity. Live, herbaceous vegetation was relatively abundant on VIC. The four LB tests were subunits of the same clearcut unit, and provided side-by-side comparison of four replicate tests (although LB2 was burned one month later than the other three). CPC was chosen because it represented a typical hardwood management unit burned under the driest woody fuel conditions (18%) of any of the hardwood units.

2. Long-needled Pine units ("LP"). The pine tests were chosen from two distinct geographical areas and pine communities. LL1 and LL2 were paired subunits within a clearcut lodgepole pine unit near Bend (central), Oregon. Fuel characteristics were nearly identical for these two tests. The CC tests, located near Leavonworth (northcentral), Washington, were paired, side-by-side subunits within a clearcut ponderosa pine unit. Fuels and conditions were nearly the same for both tests.

3. Mixed-conifer units ("MC"). Three units--RSP, WHH, HESS--were burned the same week in similar fuel conditions near LaGrande (northeast), Oregon. The WHH unit had roughly 40 percent more fuel than the other two. The higher fuel loading on WHH was due primarily to the presence of more logs (rather than to larger material) with a coincident increase of 40 percent in number of rotten logs.

4. Tractor/dozer-piled slash ("TP"). All dozer-piled tests were at the same site in northwestern Washington, and were constructed from mixed conifer slash piled by a bulldozer tractor. PIL1 and PIL2 were of similar mass and fuel characteristics, PIL4 was nearly twice as large, and volume and mass in PIL3 was "in between".

5. Crane-built piles ("CP"). These piles were constructed from mixed conifer slash using a crane. SKY1 contained typical 2nd-growth slash primarily in the 8"-18" diameter range, with fine fuels (1/4"-1") well mixed throughout. SKY2 contained large old-growth debris with occasional rotten logs throughout--all logs were stacked parallel--and had the greatest mass of the four piles. SKY3 and SKY4 were constructed as paired tests, with well distributed sizes of materials stacked in classic "teepee-shaped" piles.

4.2 Description of Sampling Apparatus

The primary sampling of emissions from test burns in each of the four fuel complexes was accomplished with five instrumentation packages (sample packages) suspended from a steel tower-and-cable support system (figure 4.2.1). When positioned in the active convection column, each of the five packages produced continuous, real time measurements of several combustion parameters and also obtained multiple grab-samples of particulate and gaseous emissions for subsequent laboratory analysis. Several additional sampling devices were also used to obtain supplemental grab-samples. All sampling devices were electronically connected and/or plumbed to a ground control station located adjacent to the test area. Reference should be made to schematic figures 4.2.2 and 4.2.3 for details of the plumbing and electrical configurations, respectively. Specifications for all of the primary sampling components and instruments are given in table 4.2.1.

The configuration of this sampling array has varied somewhat from one year to the next due to equipment failures, modifications, and improvements. The method by which the sample packages were suspended in the convection column varied as well, and was dependent on the terrain encountered and fire behavior expected in each of the fuel types. However, consistency in the measurement objectives and in

sampling protocols for each parameter was strictly maintained for all tests.

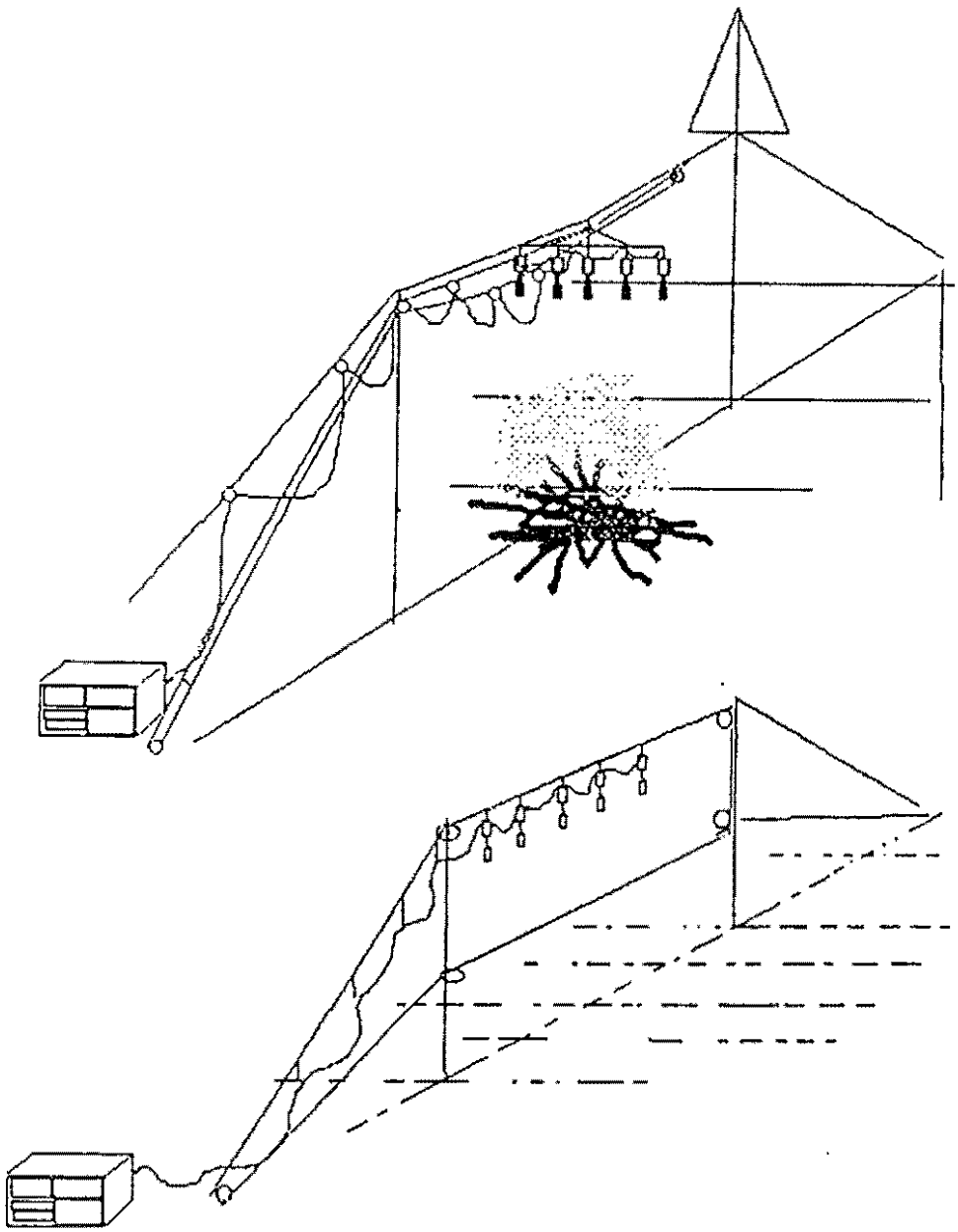


Figure 4.2.1. Configuration of the sampling array suspended above a pile (upper), and a clearcut (lower).

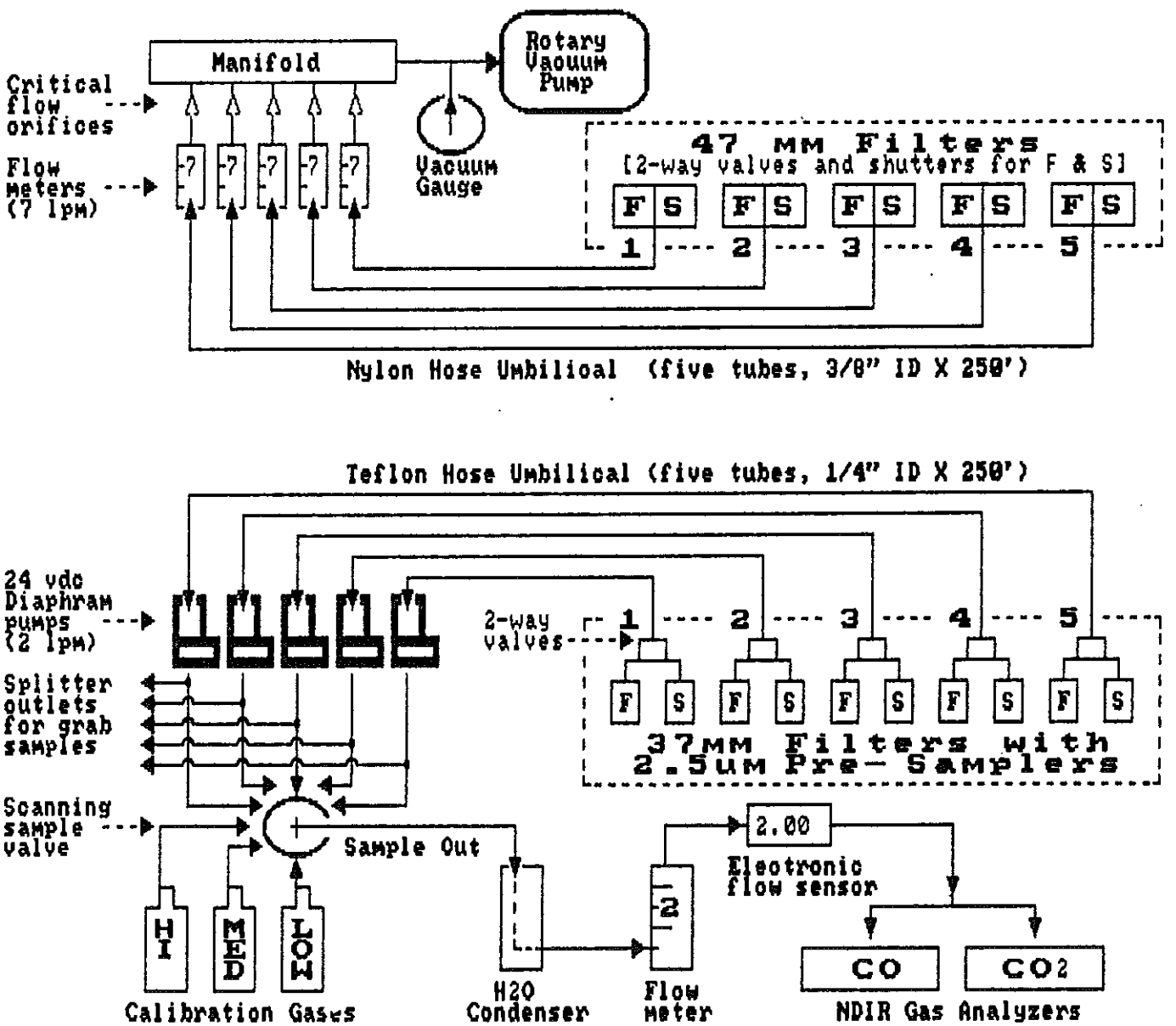


Figure 4.2.2. Schematic of the tubing and gas-train configuration used for real time measurements and "grab sampling" of emissions.

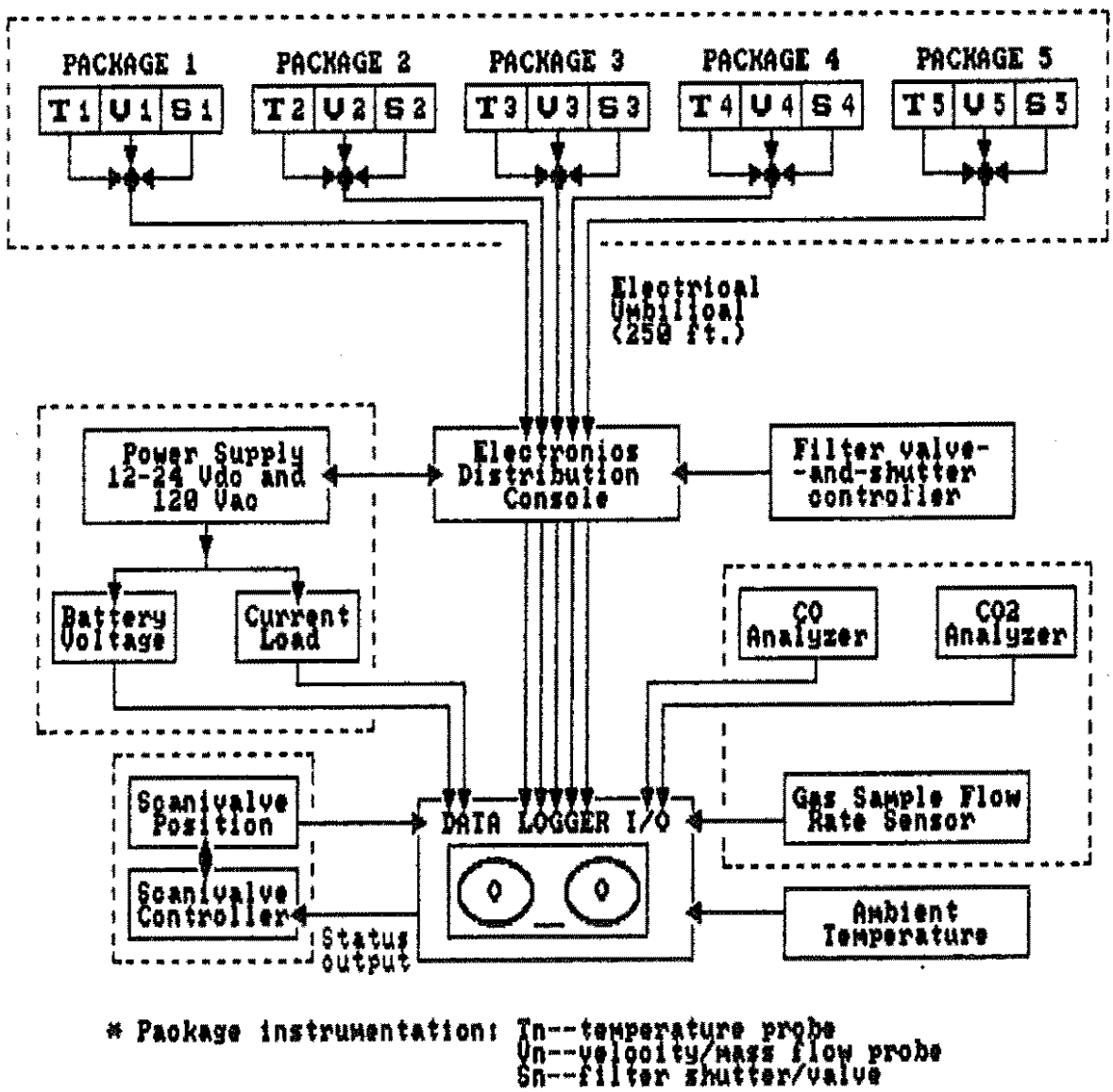


Figure 4.2.3. Schematic of analog-to-digital input/output and electrical configuration for real time sampling system.

Table 4.2.1. Specifications for sensors, instruments, and control systems used in field sampling and laboratory analyses.

MEASUREMENT PARAMETER	APPLICATION GRAB	APPLICATION REAL	SENSOR MANUFACTURER AND MODEL	MEASUREMENT TECHNIQUE	RANGE (90% FULL SCALE)	APPROXIMATE ACCURACY	ANALOG OUTPUT
Data Acquisition	X	X	John Fluke Mfg. Co. Inc; Model 2280A Data Logger	Analog-to-digital I/O and control	N/A	±.01%	N/A
Carbon monoxide	X	X	Horiba Instr. Inc; Model PIR-2000	NDIR	0-2000 PPM	±.5%	0-100 mv
Carbon dioxide	X	X	Horiba Instr. Inc; Model PIR-200	NDIR	0-5000 PPM	±.5%	0-100 mv
CH4, NMHC	X		Baseline Ind., Inc; Model P1030A	GC	N/A	±2.0%	0-100 mv
Vertical mass flow (pack. 2,4)		X	Kurz Instr. Inc; Model 450-DC-SP-HTT	Temperature-compensated thermal anemometer	0-15 MPS	±.25%	0-6 vdc
Vertical airspeed (pack. 1,3,5)		X	Qualimetrics; Model 24201	Vane anemometer	0-10 MPS	±3.00%	0-30 vac
Temperature		X	Chromel-alumel with Omega Engineering Inc. electronic ice point; Model MCJ-K	Thermocouple	0-1250 °C	±1.00 °C	0-50 mv
Electro-balance	X		Cahn Instr. Inc; Model 28	Closed loop electro-mechanical	A.200 mg B.1000 mg	±1.00 µg ±10.00 µg	Display and BCD
Vacuum pump for 7 LPM, 47mm filters	X		Gast Mfg. Corp; Model 3040V-29B	Rotary carbon vane vacuum pump	35 LPM at 25" Hg.	Volume through each filter regulated by critical-flow orifice	
Vacuum pump for each 2 LPM, 37mm filter and gas analyzers	X	X	ASF Inc; Model 7010-D	12 vdc diaphram pump, one for each filter (6)	1-10 LPM	Volume regulated by voltage adjustment and micro-valve	

4.2.1 Particulate Matter Sampling

Particulate matter was sampled for each phase of combustion on four kinds of filter media in a total of three different sizes (and volume flows). This was necessary because of the matrix of analyses performed on the particulate matter. Each of the five sample packages were fitted with duplicate sets of filters, with each set consisting of one 47-mm filter head and one 37-mm filter head. The two sets were

exposed sequentially with valve and shutter devices to obtain particulate samples for both the flaming and first smoldering combustion phases on separate filters before the packages were retrieved and fitted with fresh filters. All of the filter-set selecting and sample volume adjustments were controlled and monitored from the ground station.

For each combustion phase, three of the 47-mm filter heads held glass-fiber filter mats and two held glass-fiber filter mats backed with polyurethane foam material (PUF samplers--used to check for breakthrough of PAH compounds). A high-capacity rotary vane vacuum pump was used to supply a constant flow of about 7 liters per minute (l/m) through the 47-mm filter heads. The vacuum was ported to the filter heads through a manifold and five nylon hoses (5/16" O.D. by 1/4" I.D.) and was regulated by maintaining a differential pressure across flow-limiting orifices of at least 0.56 atmospheres.

The 37-mm filter holders used a cyclone presampler to provide a mean mass diameter cutpoint of 2.5 micrometers. For each combustion phase, three of the 37-mm filter holders contained glass-fiber filters and two contained stretched teflon with polyolefin rings. Five 24-volt d.c. diaphragm pumps were used to supply vacuum through individual teflon hoses (1/4" O.D. by 3/16" I.D.) to the 37-mm filter holders on each sample package. A constant volume flow of 2 l/m was maintained throughout the sampling period by controlling the voltage to each respective pump and with low-pressure regulating valves. Flow was referenced to a calibrated rotameter and to an electronic flow sensor.

An 8- by 10-inch glass fiber filter mat fitted to a high-volume sampler was used for collecting samples of the particulate matter by combustion phase for the analysis of POMs. The sampler was suspended adjacent to package #1 and

a volume flow of 40 cubic feet per minute was automatically regulated by an electronic mass flow controller. Immediately after collection the filter mats were wrapped in foil and were stored in a cool, light-tight container.

4.2.2 Content of the Particulate Matter

Trace elements, PAH compounds, B[a]P, light absorption, and carbon analyses were performed on the samples of PM and PM2.5 collected for each combustion phase by fire. The analyses and laboratories involved in the work are shown by figure 4.2.4. These laboratories are as follows:

1. Graphytic carbon and total carbon analyses were done under contract to the Sunset Laboratory (Robert A. Cary), 2017 - 19th Ave., Forest Grove, OR 97116 (Tel: 503/357-5151).

2. Polycyclic organic matter (POM) and polycyclic aromatic hydrocarbon (PAH) fractionation and profiling of compounds were performed through the USDA, Tobacco Safety Laboratory, Athens, GA, with passthrough money to the Southern Forest Fire Laboratory, USDA Forest Service, Macon GA.

3. Trace element analyses (using protocol 4) were contracted for with NEA Laboratories (John A. Cooper), 8310 SW Numbus, Beaverton, OR 97005 (Tel. 503/643-4661).

4. Trace ions including SO_4, NO_3, and NH_4 were performed by E. Heyerdahl in cooperation with Cloud Aerosol Physics Group at University of Washington.

5. Light absorption and a second measurement of the graphitic carbon content of the PM were accomplished through cooperative agreement with Dr. E.M. Patterson, School of Geophysical Sciences, Georgia Institute of Technology, Atlanta, GA 30332-0340 (Tel. 404/894-3898). This work was done through an agreement negotiated with the Defense Nuclear Agency.

4.2.3 Combustion gases were sampled from each of the five teflon tubes connected to the sample packages. For each of the phases of combustion, flow-restricting splitter outlets

at the ground station were used to collect a portion (.05-.20 l/m) of the 2 l/m sample volume from each package in 5-liter aluminized-mylar gas sample bags. The remainder of the 2 l/m gas stream from each package was ported to a scanning sample valve (scanivalve). The scanivalve sequentially directed each gas stream (25 seconds per package) through a divider to two nondispersive infrared gas analyzers for analysis in real time of CO and CO_2 concentrations. The gas analyzers were calibrated periodically before, during, and after each test using certified calibration gases traceable to National Institute of Standards and Technology reference gases.

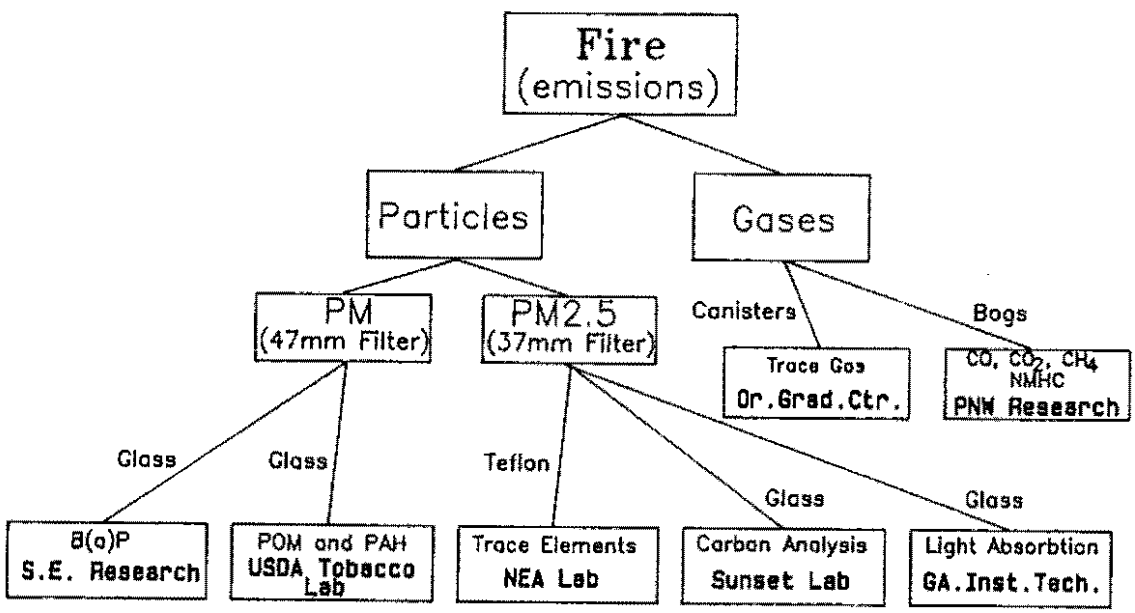


Figure 4.2.4. Flow chart of laboratory analyses performed on sampled gases and particles.

Trace gases such as the light molecular weight halogenated species CH_3Cl, CH_3I, CH_3Br and several other species (CH_4, CO, N_2O, H_2) were quantitatively measured through cooperative work with the Oregon Graduate Center, R.A. Rasmussen, 19600 NW Walker Road, Beaverton, Oregon.

4.2.4 Temperature of the Combustion Gases

The temperature of the combustion gases near each package was measured using chromel-alumel thermocouples. The thermocouples in each package were referenced to 0 deg. C. by electronic ice-point reference junctions, and an analog voltage (mV d.c.) was transmitted through an electrical umbilical to the ground station. Other system temperatures were similarly measured, including the test area ambient temperature and the temperature of the gas stream at the exit point of a heat exchanger installed in package #3.

4.2.5 Velocity of the Vertical Component

The velocity of the vertical component of the combustion gases (convection column) was measured in real time at each package location. Vane anemometers were installed in packages #1, #3, and #5. Mass flow sensors were installed in package #2 and Package #4. The mass flow sensors are temperature-compensated thermal anemometers and have much lower startup threshold limits for sensing low velocities. The vane anemometers have a 0.5-meter per second startup threshold, but are more responsive in high velocities where the air movement is accompanied by a high radiant heat load. The emissions trajectory in the vertical dimension was not always vertical. To control for the horizontal vector components, the velocity sensors were shielded in the horizontal component by tubular metal shrouds. Wind tunnel tests have demonstrated that the shrouds provided a cosine response to wind speed as the shrouded sensors were rotated

90 degrees from the horizontal to the vertical axis (Ward et al. 1982). Each velocity sensor transmitted an analog voltage through an electrical umbilical to the ground station. All velocity sensing instruments were periodically calibrated in a wind tunnel using a reference standard anemometer.

4.2.6 Data Acquisition and Control

A data acquisition and control system (data logger) at the ground station was used to manage each of the sensor analog outputs, system status, scanivalve control, and real time data recording. For the duration of each test, the data logger interrogated each of the sensors and instruments on two-second intervals, performed analog-to-digital conversions and math procedures, and recorded the data with time stamp information on magnetic tape. The status of any input or output channel could be monitored, printed, or plotted at any time. In addition, the data logger controlled the scanivalve activation to obtain sequential gas samples from each of the sample packages on 25-second intervals for real time CO and CO_2 analyses.

4.2.7 Mechanical Support System

A tower and cable support system was configured in several ways for positioning the five sample packages and the electrical-and-hose umbilical in the convection column(s). The particular configuration was dependent on the terrain, fuel arrangement, and expected fire behavior associated with the fuel complexes. The emissions sampling geometry was defined to allow for mass flux calculations and to accommodate for cases where the emissions trajectory was not vertical. Subsequent derivations of emission factors (EF) and source strength (q) values were obtained through manipulations of the calculations listed in section 4.3.

While the area actually sampled was often 0.5 hectare or larger, the results of emissions flux and fuel consumption calculations are expressed on a unit area basis of one square meter.

The support system used for the broadcast burn tests suspended the packages on moveable cables strung between two steel towers erected approximately 20 meters tall and spaced approximately 50 meters apart (figure 4.2.1). The packages were spaced 7 meters apart and were supported at the highest level (approximately 21 meters) for the flaming (F) phase of combustion. The packages were lowered to a height of approximately 10 meters for the smoldering (S1, S2) combustion phases.

Sampling of emissions from piled logging slash was accomplished by suspending the packages between the towers on a 10-meter bar attached to a carriage (figure 4.2.1). The carriage was repeatedly traversed above the burning piles to obtain cross-section averaged measurements of the convection column.

4.3 Calculated Parameters

Gas and particulate matter concentrations were measured on volume-to-volume and mass-to-volume bases, respectively. The carbon was first converted to mass of carbon produced per unit volume from all of the measured combustion products (expressed in units of mg/m^3). A basic assumption was that the carbon in the fuel was uniformly converted to carbon in the emissions during combustion. In general, a second assumption was that the emissions were well mixed in the atmosphere.

The following parameters were computed for the data:

1. Emission factors (EF_n) for each emission ($_n$).
2. Emission flux (source strength) for each emission using two techniques.
3. Rate of fuel consumption.
4. Cumulative consumption of fuels.
5. Cumulative emissions produced.
6. Fire intensity or rate of heat released per unit area.
7. Total energy released.
8. Combustion efficiency.

4.3.1 Calculation of Emission Factors

The carbon-mass balance method of assessing the fuel consumed that produced the emissions was employed for all the emission factors calculated in this report after the technique was first used successfully under field conditions by Ward and colleagues (1982). The method is based on the stoichiometric partial oxidation of fuel ($C_6H_9O_4$) to products of CO_2 and incomplete combustion. The carbon contained in the fuel is about 50 percent of the mass of the fuel. The measured carbon contained with the combustion products is multiplied by 2 to calculate the mass of fuel consumed in producing the combustion products. Emission factors are calculated by dividing the mass of emission by the fuel consumed and expressed in units of g/kg.

Emission factors were calculated based on the mass of emission produced per mass of fuel consumed. The CMB method was used exclusively to determine the mass of fuel consumed in producing the emissions. Basically, the CMB accounts for

the carbon released from the fuel during combustion by measuring the concentration of the carbon-containing combustion products. The fuel consumed was computed based on the sum of C_n from the combustion products as follows:

$$W_V = (\Sigma C_n)/R; \quad (1)$$

where,

W_V = fuel consumed, g/m^3,

C_n = the carbon fraction of the emission n, g/m^3,

n = CO_2, CO, NMHC, CH_4, PM, and

R = the carbon fraction of the fuel elemental analysis.

It immediately follows that an EF for a specific emission, E_n, can be computed by dividing the mass of E_n contained in a unit volume by the total fuel consumed in producing the emissions within the unit volume as follows:

$$EF_{n[p]} = E_{n[p]}/W_V; \quad (2)$$

where,

$EF_{n[p]}$ = emission factor of the emission n, g/kg,

$E_{n[p]}$ = concentration of emission n, mg/m^3, and

[p] = phase of combustion--F, S1, S2 or blank (if for entire fire).

4.3.2 The rate of fuel consumption during the fire was measured by the carbon flux technique. By measuring the concentration of carbon, converting the carbon to fuel according to equation (1), and multiplying the fuel per unit volume by the vertical velocity of the emissions, the resulting flux represents the rate of fuel consumption (with

units of mass per unit area per unit time), as follows:

$$\dot{w} = (W_V)(V_Z); \quad (3)$$

where,

$\dot{w}$ = rate of fuel consumption, $g/m^2/s$, and

V_Z = vertical velocity of plume, m/s.

Cumulative fuel consumption is calculated by integrating the rate of fuel consumption curve from time i to j as follows:

$$W = \int_i^j \dot{w}dt \approx \sum_i^j \dot{w}(t_{i+1}-t_i) \quad (4)$$

where,

W = total fuel consumed, g/m^2, and

t_i and t_{i+1} = actual times during the fire of sufficient proximity so that w has not changed significantly.

4.3.3 Rate of Energy Release

4.3.3.1 Carbon flux.-- The rate of energy release (reaction intensity) can be computed by multiplying the rate of fuel consumption by the heat of combustion, then subtracting the reduction in heat released from the compounds not oxidized completely. This heat release rate is calculated as follows:

$$I_r = \dot{w}(H-B) \quad (5)$$

where,

I_r = rate of energy release, kW/m^2,

H = heat of combustion, kJ/kg, and

B = energy lost due to incomplete combustion, radiation, and absorption into the soil, kJ/kg.

4.3.3.2 Energy balance.-- An alternative calculation of the energy yield of the fires can be made by measuring the temperature concurrently with the velocity. The heat flux from the fire is computed using the vertical velocity in the convection column, difference in temperature between ambient air and the convection column gases, specific heat of air, and density of air. A linear relationship was derived for the specific heat of smoke at different temperatures from known specific heats of air, carbon dioxide, and carbon monoxide. The flux of heat from the fire (reaction intensity) is expressed on the basis of a square meter of area burned, in units of kW/m^2, and can be computed as follows:[3]

$$\dot{q} = V(T-T_a)C_{air}P \qquad (6)$$

where,

$\dot{q}$ = heat flux from the fire, kW/m^2,
V = vertical velocity, 30 second average, M/s,
T = plume temperature, 30 second average, °K,
T_a = ambient (precombustion) temperature, °K,
C_{air} = specific heat of smoke (calculated), kJ/kg,
P = density of smoke (calculated), kg/m^3.

4.3.4 Combustion Efficiency

Combustion efficiency (ϕ) is defined in terms of the ratio of carbon converted to the most highly oxidized form--CO_2. It is a calculated parameter normally ranging from 0.60 to 0.95.

---

[3]Derivations and proofs were performed by Ms. Jenifer Long. Copy on file, Seattle Forestry Sciences Laboratory, Seattle, Washington, 1988.

If the carbon from the woody fuels were converted stoichiometrically to CO_2, then the emission factor for CO_2 would be 1835 g/kg. If the fuel undergoes incomplete combustion, then a portion of the carbon is converted to other combustion products. Hence, the emission factor for CO_2 is reduced from the theoretical by the amount of carbon that is converted to other products (CO, CH_4, NMHC, and PM). By dividing the measured EF_{CO2} by the theoretical EF_{CO2}, the combustion efficiency can be calculated:

$$\phi = \frac{EF_{CO2}\ \text{actual}}{EF_{CO2}\ \text{theoretical}} \qquad (7)$$

where,

ϕ = combustion efficiency, dimensionless, and

EF_{CO2} = emission factor for CO_2, g/kg.

4.3.5 Weighting of Emission Factors

Emission factors averaged to represent an entire fire (fire-weighted averages) were weighted using one of two different methods, depending on whether it was a primary combustion product such as CO, CO_2, PM, etc. or if it was a subcomponent of another emission (for example, a PAH compound attached to the PM2.5).

Emission factor values for the primary combustion products were weighted based on the amount of fuel consumed during each of the sampling periods as follows:

$$EF_n=((EF_{n[F]})(W_{[F]})+(EF_{n[S1]})(W_{[S1]})+(EF_{n[S2]})(W_{[S2]}))/(W_{[F]}+W_{[S1]}+W_{[S2]}) \qquad (8)$$

For those components that were a function of the mass of PM2.5 produced (the trace elements, carbon, and PAH components) the values for the specific subcomponent (n) were weighted dependent on the mass of PM2.5 produced as follows:

$$\%n=[(\%n_{[F]})(W_{[F]})(EF_{PM2.5[F]}) + (\%n_{[S1]})(W_{[S1]})EF_{PM2.5[S1]}) + (\%n_{[S2]})(W_{[S2]})(EF_{PM2.5[S2]})] / \text{Total PM2.5} \quad (9)$$

where,

- n = emission subcomponent
- F = flaming combustion phase
- S1 = first smoldering combustion phase
- S2 = second smoldering combustion phase

5.0 RESULTS

The primary data discussed in this report are presented in Appendix A (concentrations), Appendix B (content of PM2.5) and Appendix C (emission factors, carbon concentration, combustion efficiency, fuel consumption, and heat release rate) for each test fire by phase of combustion. Concentrations of the primary combustion gases are discussed along with the mass concentration of particles without regard to size (PM) and the mass concentration of particles less than 2.5 micrometers mean mass cutpoint diamter (PM2.5). Chemical analyses of the particulate matter samples provided additional information regarding the fractional composition of the particles according to important classes of materials. These include: trace metals, graphitic and organic carbon content, and polynuclear organic materials content. Also presented are data describing several important trace gases.

5.1 Grab Samples

5.1.1 Primary Gases--Concentrations

Primary combustion gas concentrations are presented for all tests in Appendix A. The concentration of carbon dioxide, carbon monoxide, methane, and nonmethane hydrocarbons are listed for the discrete sample periods by test. A summary of the range of concentrations for each of the gases by combustion phase is provided in table 5.1.1. The highest fire-average CO_2 concentration was for the DF tests--also the highest flaming phase concentrations. The piled slash tests exhibited the lowest CO_2 concentrations, with the CP tests averaging 75% lower than the DF tests. Carbon monoxide values varied similarly, with the highest and lowest values attributed to DF and CP tests, respectively. Concentrations of CH_4 and NMHC were quite similar between DF

and HW, and the values for those two fuel types together were higher than for the other fuel types; piled slash tests being the lowest.

Table 5.1.1. Concentrations of gases for each phase of combustion, by fuel type.

		Concentration (PPM) of Gases					
Gas	Phase	-----DF-----	-----HW-----	-----LP-----	-----MC-----	-----TP-----	-----CP-----
CO	flame	139.8 ± 50%	69.0 ± 90%	82.5 ± 34%	29.8 ± 48%	16.4 ± 64%	18.2 ± 41%
	smold	103.6 ± 85%	68.7 ± 56%	36.6 ± 37%	60.9 ± 28%	31.7 ± 60%	33.4 ± 26%
	fire	185.7 ± 46%	117.6 ± 48%	92.5 ± 27%	80.5 ± 36%	46.7 ± 94%	30.6 ± 15%
CO2	flame	2301.0 ± 55%	1637.4 ± 69%	1995.9 ± 20%	1234.2 ± 13%	872.0 ± 88%	387.2 ± 5%
	smold	425.2 ± 85%	395.8 ± 60%	243.0 ± 14%	442.2 ± 33%	260.6 ± 53%	274.0 ± 6%
	fire	1434.2 ± 87%	956.1 ± 60%	1073.2 ± 19%	794.4 ± 13%	537.8 ± 75%	329.0 ± 5%
CH4	flame	7.6 ± 61%	5.9 ±106%	4.8 ± 33%	2.9 ± 62%	1.5 ± 73%	3.0 ± 26%
	smold	6.6 ± 89%	6.3 ± 55%	3.3 ± 18%	7.1 ± 40%	4.3 ± 62%	7.6 ± 23%
	fire	10.9 ± 45%	10.8 ± 50%	7.5 ± 8%	9.0 ± 42%	6.2 ± 95%	6.3 ± 14%
NMHC	flame	2.5 ± 60%	2.5 ± 96%	2.1 ± 33%	1.2 ± 58%	0.5 ± 80%	1.0 ± 20%
	smold	1.4 ±100%	1.8 ± 50%	0.8 ± 50%	1.9 ± 31%	1.0 ± 60%	1.8 ± 16%
	fire	2.8 ± 64%	3.2 ± 53%	2.1 ± 33%	2.5 ± 32%	1.5 ± 86%	1.6 ± 6%

5.1.2 Particulate Matter--Concentrations

The particulate matter concentrations are listed for the discrete sample periods by test in Appendix A. The listing is formatted similarly to that of the primary combustion gases. The ranges of concentration of particulate matter without regard to size (PM) and the concentration of particles with mean mass cutpoint diameters of less than 2.5 micrometers (PM2.5) are listed in table 5.1.2. Average concentrations of both PM and PM2.5 were consistently higher for the DF type than for any other--six times higher than for the crane-piled tests.

Table 5.1.2. Concentrations of particulate matter (PM and PM2.5) for each phase of combustion, by fuel type.

Size	Phase	Concentration (Mg/m3) of Particulate					
		----DF----	----HW----	----LP----	----MC----	----TP----	----CP----
PM	flame	23.4 ± 58%	12.2 ± 27%	20.1 ± 36%	13.6 ± 64%	5.8 ±101%	4.7 ± 29%
	smold	9.6 ± 98%	9.6 ± 67%	9.3 ± 52%	8 ± 2%	3.7 ± 70%	7.3 ± 30%
	fire	20.1 ± 46%	18.4 ± 45%	23 ± 21%	12.9 ± 33%	5.4 ± 64%	6.9 ± 13%
PM2.5	flame	14.3 ± 54%	6.2 ± 41%	11 ± 65%	6.2 ± 35%	3.1 ±103%	2.6 ± 68%
	smold	8.3 ± 79%	5.9 ± 66%	5.2 ± 48%	5.8 ± 17%	1.2 ± 83%	5.1 ± 17%
	fire	14 ± 38%	11.3 ± 47%	12.8 ± 16%	8.5 ± 34%	3.1 ± 96%	4.4 ± 11%

5.1.3 The content of PM2.5 is presented by phase for each test in Appendix B. Content of PM2.5 is a function of the chemistry of the fuels burned and the fire behavior. Figure 5.1.3 illustrates the difference in content of the fine particles on a percentage basis for the six fuel types burned. The relative percentage of emissions produced by phase of combustion may be partially responsible for the differences between fuel types. The difference between the content of oxygen, hydrogen, and nitrogen for the tractor-piled and crane-piled slash appears negligible. However, the difference in trace element and graphitic carbon content is quite large for these two fuels.

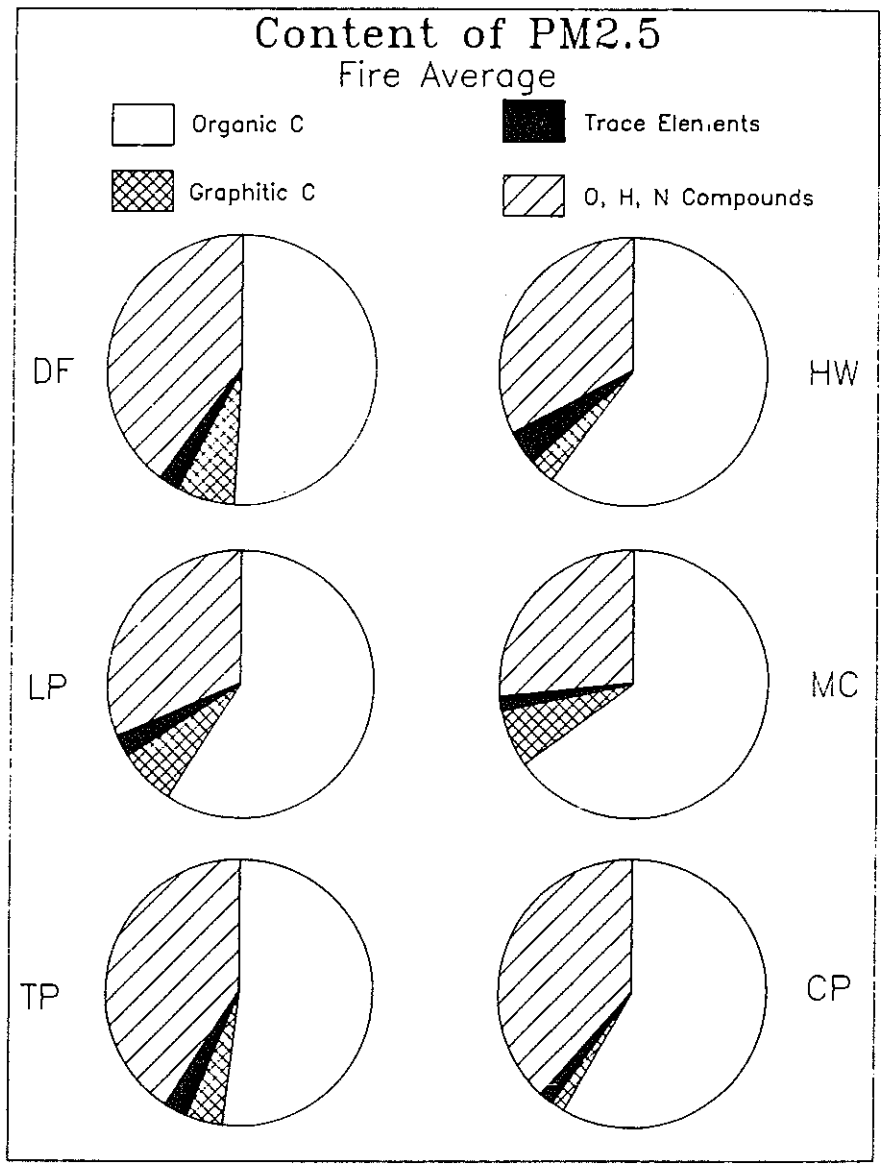


Figure 5.1.3. The content of the fine particles (PM2.5) for the six fuel types studied. Shown here are fire-averaged values for organic carbon, graphitic carbon, trace elements, and other compounds.

5.1.3.1 Trace elements.-- The trace element content of the PM2.5 is listed in Appendix B (tables B.1 - B.6) for each of the trace metals. The ranges of trace element composition of the PM2.5 is summarized by fuel type for each phase of combustion in tables 5.1.3a - 5.1.3c.

5.1.3.2 Graphitic and organic carbon.-- Graphitic and organic carbon content of the PM2.5 is also listed in Appendix B (tables B.7 - B.12). The range of carbon composition of the PM2.5 particles is summarized by fuel type for each phase of combustion in tables 5.1.3a - 5.1.3c.

Table 5.1.3a. Trace element and carbon content of the PM2.5 for each fuel type for the flaming phase.

	Percent of PM2.5 -- Flaming Phase																					
Element	DF			HW			LP			MC			TP			CP						
Na	2.734	±	134%																			
Al	0.120	±	68%	0.280	±	154%	0.081	±	47%	0.119	±	17%	0.181	±	46%	0.025	±	34%				
Si	0.091	±	69%	0.427	±	121%	0.152	±	54%	0.107	±	2%	0.348	±	33%	0.016	±	200%				
P				0.237	±	106%	0.088	±	39%	0.148	±	22%	0.128	±	30%	0.011	±	35%				
S	0.341	±	42%	1.118	±	108%	0.656	±	52%	0.570	±	23%	0.950	±	53%	0.229	±	15%				
Cl	0.556	±	56%	2.703	±	117%	0.564	±	60%	0.739	±	53%	0.921	±	37%	0.196	±	13%				
K	1.419	±	66%	5.014	±	123%	2.103	±	55%	2.812	±	42%	3.895	±	59%	1.195	±	17%				
Ca	0.182	±	126%	0.181	±	218%	0.112	±	45%	0.151	±	42%	0.619	±	22%	0.074	±	25%				
Ti	0.218	±	101%	0.019	±	164%	0.010	±	96%	0.008	±	41%	0.018	±	96%	0.001	±	118%				
V	0.069	±	176%	0.006	±	150%	0.003	±	94%	0.004	±	67%	0.007	±	81%	0.001	±	142%				
Cr	0.113	±	171%	0.018	±	238%	0.003	±	175%	0.004	±	54%				0.000	±	250%				
Mn	0.038	±	88%	0.023	±	129%	0.016	±	46%	0.028	±	45%	0.045	±	66%	0.019	±	24%				
Fe	0.057	±	179%	0.107	±	211%	0.010	±	76%	0.017	±	35%	0.030	±	68%	0.006	±	71%				
Ni	0.009	±	67%	0.024	±	225%	0.005	±	106%	0.001	±	83%	0.011	±	116%	0.000	±	200%				
Cu	0.009	±	67%	0.021	±	175%	0.000	±	200%	0.002	±	0%	0.007	±	134%	0.001	±	50%				
Zn	0.118	±	79%	0.154	±	120%	0.115	±	60%	0.208	±	33%	0.389	±	57%	0.054	±	37%				
Br	0.048	±	44%	0.124	±	84%	0.033	±	78%	0.033	±	27%	0.146	±	71%	0.004	±	67%				
Ag				0.077	±	202%	0.028	±	62%	0.060	±	55%	0.172	±	73%	0.005	±	85%				
Cd				0.169	±	234%	0.046	±	106%	0.094	±	37%	0.066	±	158%	0.001	±	188%				
Sn				0.086	±	195%	0.013	±	117%	0.045	±	131%	0.196	±	92%	0.005	±	200%				
Pb	0.154	±	63%	0.211	±	175%	0.068	±	100%	0.033	±	56%	0.234	±	86%	0.007	±	116%				
Carbon																						
OC	36.425	±	30%	60.275	±	3%	55.050	±	7%	57.666	±	1%	49.000	±	10%	59.825	±	7%				
EC	18.819	±	67%	8.275	±	56%	10.900	±	60%	28.435	±	28%	8.175	±	46%	2.300	±	15%				
TC	55.044	±	7%	68.550	±	5%	65.950	±	6%	86.101	±	10%	57.175	±	9%	62.125	±	7%				

Table 5.1.3b. Trace element and carbon content of the PM2.5 for each fuel type for the smoldering phase.

	Percent of PM2.5 -- Smoldering Phase				
Element	DF	HW	LP	MC	TP	CP
Na	0.732 ± 66%					
Al	0.101 ± 96%	0.181 ± 89%	0.105 ± 65%	0.030 ± 32%	0.056 ± 12%	0.013 ± 58%
Si	0.167 ± 117%	0.336 ± 121%	0.148 ± 115%	0.043 ± 37%	0.052 ± 47%	0.013 ± 89%
P		0.093 ± 84%	0.048 ± 48%	0.041 ± 35%	0.039 ± 18%	0.007 ± 52%
S	0.114 ± 57%	0.503 ± 98%	0.162 ± 68%	0.081 ± 76%	0.228 ± 18%	0.125 ± 40%
Cl	0.118 ± 53%	0.468 ± 46%	0.226 ± 74%	0.115 ± 56%	0.227 ± 7%	0.107 ± 43%
K	0.126 ± 49%	0.677 ± 97%	0.501 ± 79%	0.293 ± 83%	0.606 ± 31%	0.818 ± 40%
Ca	0.127 ± 81%	0.183 ± 187%	0.073 ± 128%	0.054 ± 52%	0.071 ± 16%	0.078 ± 23%
Ti	0.124 ± 72%	0.013 ± 103%	0.005 ± 156%	0.003 ± 38%	0.002 ± 100%	0.002 ± 60%
V	0.031 ± 79%	0.004 ± 136%	0.002 ± 120%	0.001 ± 128%	0.001 ± 66%	0.000 ± 149%
Cr	0.024 ± 65%	0.003 ± 128%	0.000 ± 200%	0.001 ± 109%		0.001 ± 100%
Mn	0.020 ± 87%	0.011 ± 120%	0.008 ± 103%	0.007 ± 66%	0.005 ± 52%	0.018 ± 34%
Fe	0.061 ± 123%	0.062 ± 139%	0.057 ± 164%	0.008 ± 54%	0.003 ± 172%	0.007 ± 33%
Ni	0.010 ± 54%	0.003 ± 144%	0.002 ± 58%	0.001 ± 116%	0.027 ± 166%	0.000 ± 250%
Cu	0.010 ± 54%	0.001 ± 137%	0.000 ± 149%	0.001 ± 92%		0.001 ± 61%
Zn	0.016 ± 60%	0.014 ± 129%	0.025 ± 76%	0.012 ± 97%	0.013 ± 39%	0.012 ± 35%
Br	0.025 ± 49%	0.019 ± 53%	0.008 ± 57%	0.003 ± 87%	0.012 ± 22%	0.002 ± 76%
Ag		0.031 ± 114%	0.018 ± 70%	0.012 ± 56%	0.008 ± 126%	0.004 ± 116%
Cd		0.066 ± 173%	0.015 ± 69%	0.016 ± 48%	0.015 ± 148%	0.004 ± 86%
Sn		0.043 ± 152%	0.018 ± 80%	0.018 ± 165%		0.001 ± 140%
Pb	0.078 ± 70%	0.031 ± 132%	0.019 ± 67%	0.004 ± 102%	0.010 ± 43%	0.003 ± 75%
Carbon						
OC	51.900 ± 16%	61.660 ± 4%	61.000 ± 4%	66.299 ± 7%	53.050 ± 4%	60.360 ± 4%
EC	3.372 ± 22%	2.740 ± 38%	4.100 ± 27%	1.936 ± 40%	2.900 ± 48%	1.075 ± 32%
TC	55.272 ± 16%	64.400 ± 5%	65.100 ± 2%	68.235 ± 7%	55.950 ± 1%	61.426 ± 4%

Table 5.1.3c. Trace element and carbon content of the PM2.5 for each fuel type for fire-averaged data.

	Percent of PM2.5 -- Fire Average					
Element	DF	HW	LP	MC	TP	CP
Na	0.947 ± 63%					
Al	0.106 ± 75%	0.181 ± 83%	0.087 ± 47%	0.046 ± 39%	0.087 ± 21%	0.019 ± 7%
Si	0.130 ± 118%	0.342 ± 120%	0.131 ± 93%	0.054 ± 30%	0.121 ± 26%	0.017 ± 53%
P		0.114 ± 89%	0.064 ± 52%	0.060 ± 41%	0.058 ± 6%	0.012 ± 35%
S	0.161 ± 31%	0.697 ± 63%	0.343 ± 52%	0.171 ± 67%	0.340 ± 9%	0.173 ± 39%
Cl	0.211 ± 56%	0.856 ± 65%	0.381 ± 59%	0.239 ± 75%	0.360 ± 14%	0.156 ± 31%
K	0.370 ± 50%	1.295 ± 123%	1.221 ± 59%	0.782 ± 81%	1.140 ± 19%	1.043 ± 41%
Ca	0.139 ± 72%	0.199 ± 187%	0.074 ± 106%	0.072 ± 54%	0.205 ± 26%	0.075 ± 23%
Ti	0.127 ± 59%	0.010 ± 94%	0.006 ± 145%	0.004 ± 40%	0.006 ± 73%	0.002 ± 50%
V	0.026 ± 55%	0.003 ± 108%	0.002 ± 139%	0.001 ± 46%	0.002 ± 50%	0.001 ± 46%
Cr	0.029 ± 41%	0.004 ± 121%	0.004 ± 152%	0.002 ± 26%		0.001 ± 0%
Mn	0.025 ± 67%	0.011 ± 115%	0.010 ± 98%	0.011 ± 62%	0.013 ± 69%	0.018 ± 34%
Fe	0.051 ± 115%	0.067 ± 122%	0.031 ± 156%	0.009 ± 31%	0.019 ± 125%	0.005 ± 52%
Ni	0.009 ± 50%	0.004 ± 109%	0.003 ± 96%	0.002 ± 50%	0.024 ± 166%	0.001 ± 85%
Cu	0.009 ± 50%	0.005 ± 146%	0.000 ± 200%	0.002 ± 0%	0.008 ± 132%	0.002 ± 0%
Zn	0.029 ± 44%	0.037 ± 130%	0.064 ± 64%	0.046 ± 86%	0.083 ± 26%	0.025 ± 39%
Br	0.029 ± 32%	0.028 ± 40%	0.019 ± 81%	0.009 ± 65%	0.032 ± 19%	0.002 ± 65%
Ag		0.024 ± 52%	0.020 ± 47%	0.019 ± 44%	0.051 ± 96%	0.007 ± 47%
Cd		0.084 ± 152%	0.035 ± 86%	0.031 ± 46%	0.021 ± 83%	0.005 ± 43%
Sn		0.039 ± 163%	0.015 ± 76%	0.018 ± 83%	0.233 ± 86%	0.007 ± 147%
Pb	0.088 ± 56%	0.033 ± 110%	0.042 ± 106%	0.010 ± 86%	0.036 ± 30%	0.004 ± 25%
Carbon						
OC	50.791 ± 11%	60.220 ± 2%	59.106 ± 3%	64.832 ± 6%	51.879 ± 5%	58.319 ± 2%
EC	6.924 ± 59%	3.076 ± 42%	6.862 ± 14%	6.945 ± 63%	4.411 ± 72%	1.603 ± 53%
TC	57.716 ± 9%	63.296 ± 3%	65.968 ± 4%	71.777 ± 7%	56.290 ± 0%	59.923 ± 3%

5.2 Real Time Data

Real time measurements of carbon monoxide, carbon dioxide, temperature, vertical velocity in the convection column were made so that calculations could be made of the carbon flux from the fire, energy flux from the fire, maximum temperatures and rates of energy release by the fire could be calculated, and other rate phenomena could be evaluated. In section 5.2, measurements of the parameters are presented along with maximum values for a number of the parameters.

5.2.1 Temperature

Temperature of the combustion gases at the height of the sample packages was measured for each of the sample locations and the analog voltages recorded by the data logger. The temperatures ranged from ambient to 300°C above ambient for the hottest fire. Major temperature excursions never lasted for more than a three minutes and are not thought to have affected the integrity of the samples collected. An example of the temperature profile of a hardwood test (unit CPC) is shown in figure 5.2.1. The peak temperature for the CPC test reached nearly 180° but lasted less than three minutes.

5.2.2 Vertical Velocity

The vertical velocity of the combustion gases was measured in two ways: (1) with a thermal anemometer and (2) with a vane anemometer. Both were mounted in shrouds to protect the velocity sensors from the horizontal component of the wind field. The vertical component of the wind field was measured and recorded with the data logger. The measured velocities were highest during periods of peak combustion which occurred during the flaming combustion period. The measured profile for the CPC tests is plotted with the

temperature data in figure 5.2.1. Velocity peaked at 13 meters per second during the flaming combustion phase for the CPC test, with much lower velocities during the smoldering combustion phase.

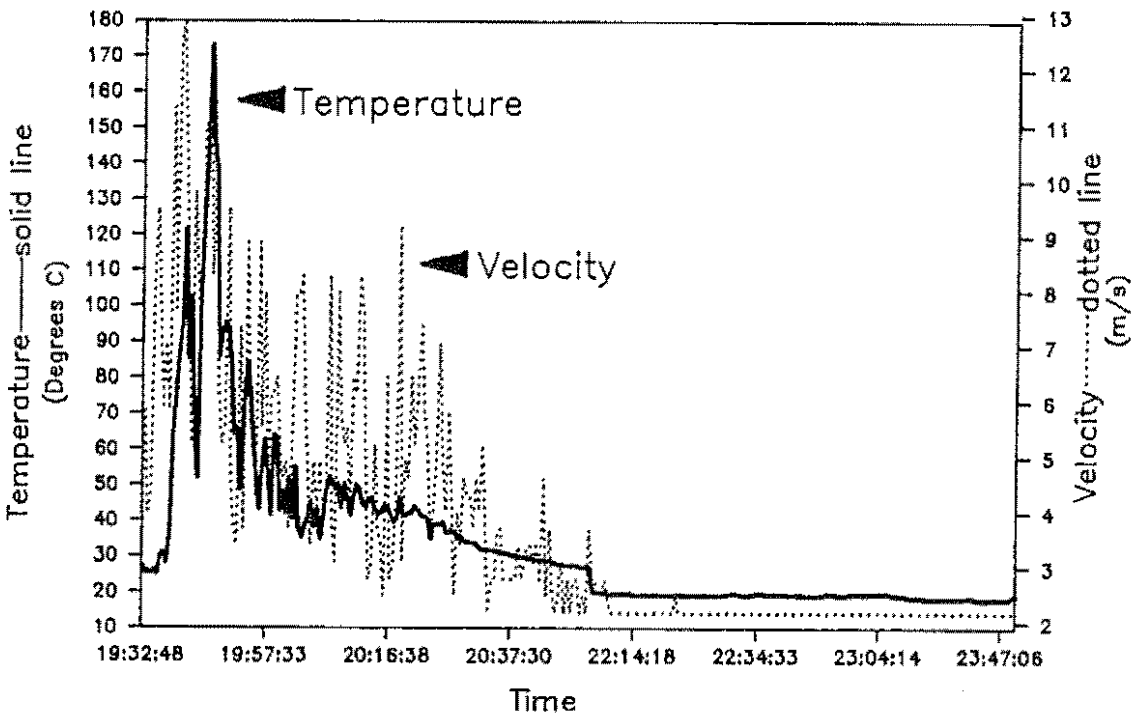


Figure 5.2.1. Real time measurements of vertical velocity and temperature, Cedar Pollard C (CPC) unit, package #3, plotted over time from ignition to extinction.

5.2.3 CO and CO_2--Concentrations

Concentrations of carbon monoxide and carbon dioxide were measured sequentially in real time over the duration of each of the experiments. Examples of the CO and CO_2 concentrations measured in real time for the CPC test are presented in figure 5.2.3. The peak CO_2 concentration reached nearly 6500 PPM and CO peaked at nearly 600 PPM. The combination of carbon monoxide and carbon dioxide accounts for over 95 percent of the carbon released from the burning fuel (fig. 5.2.4). The concentrations of both carbon monoxide and carbon dioxide were needed to measure the flux of carbon from the fires so that rates of fuel consumption could be computed.

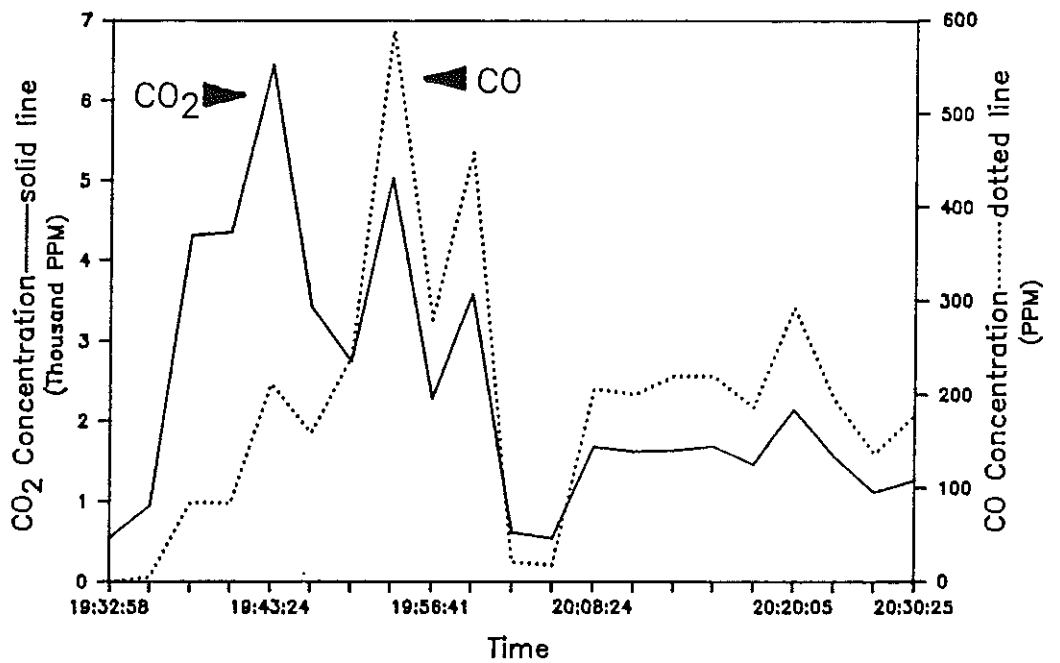


Figure 5.2.3. Real time measurements of carbon monoxide and carbon dioxide concentrations, Cedar Pollard C (CPC) unit, package #3, plotted over time for one hour following ignition.

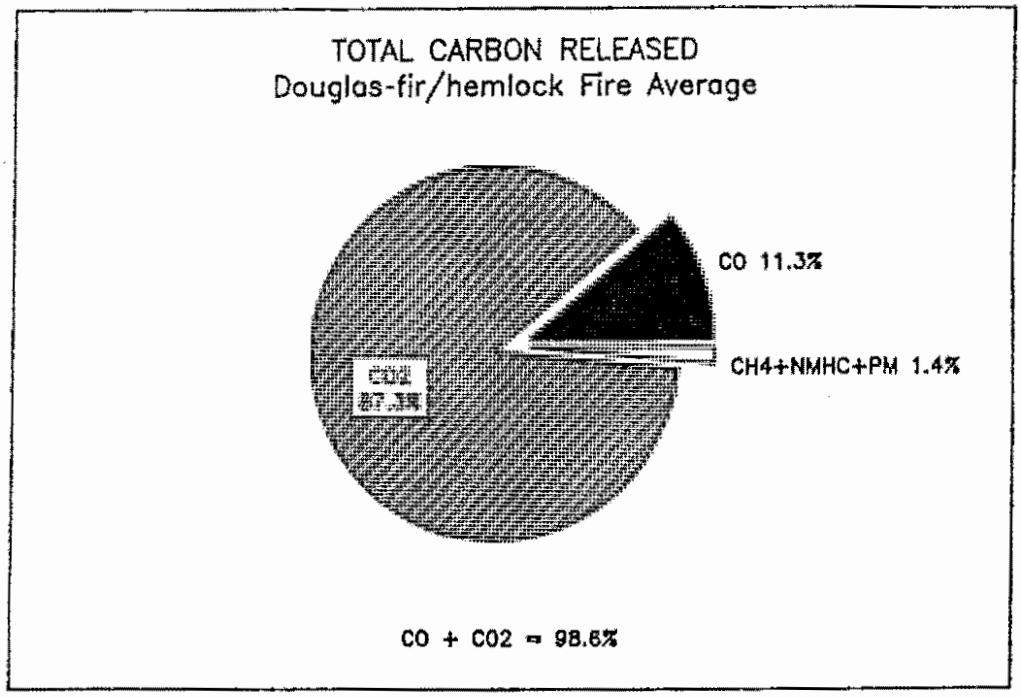


Figure 5.2.4. Carbon dioxide and carbon monoxide account for over 95 percent of the total carbon released from the burning fuel.

5.3 Calculated Parameters

Procedures for calculating emission factors, rate of fuel consumption, rate of energy release, and combustion efficiency were discussed in the methods section (section 4.0). All of these methods are dependent on the carbon mass balance and flux techniques. The emission factors are defined as the mass of emission produced per unit mass of fuel consumed. Rate of fuel consumption is dependent on multiplying the concentration of carbon in the emissions above the fire by the velocity of the gases and correcting this for the carbon content of the fuels consumed. The rate of energy release can be estimated by multiplying the rate of fuel consumption by the heat value for the fuel being burned. Combustion efficiency was defined as the ratio of actual carbon dioxide produced to the theoretical carbon dioxide production based on complete conversion of carbon contained in the fuel to carbon dioxide.

5.3.1 Emission Factors

The emission factors for the following subsections are presented in tabular format in Appendix C by test area by phase of combustion. Included in the tables of emission factors in Appendix C are data for total carbon concentrations, net fuel consumption during each sampling period, and rate of energy release (I_R). Emission factors for the primary emissions--CO, CO_2, CH_4, NMHC, PM, PM2.5--are summarized in table 5.3.1 for each fuel type by phase of combustion.

Table 5.3.1. Emission factors for the primary emissions, for each fuel type, by phase of combustion.

		Emission Factors (g/kg) for Primary Emissions					
EF	Phase	-----DF-----	-----HW-----	-----LP-----	-----MC-----	-----TP-----	-----CP-----
EFCO	flame	71.5 ± 36%	45.8 ± 34%	44.5 ± 29%	26.5 ± 46%	22.1 ± 76%	50.3 ± 42%
	smold	231.5 ± 25%	182.9 ± 32%	142.4 ± 34%	136.5 ± 19%	116.0 ± 11%	116.1 ± 17%
	fire	156.2 ± 24%	128.1 ± 17%	89.2 ± 31%	100.7 ± 30%	76.6 ± 30%	92.7 ± 9%
EFCO2	flame	1692.3 ± 3%	1694.7 ± 2%	1700.6 ± 2%	1729.0 ± 1%	1746.0 ± 2%	1674.7 ± 3%
	smold	1401.8 ± 6%	1425.5 ± 9%	1486.5 ± 6%	1511.3 ± 4%	1561.8 ± 2%	1611.1 ± 3%
	fire	1541.0 ± 5%	1536.1 ± 3%	1600.9 ± 3%	1582.7 ± 4%	1636.6 ± 3%	1671.7 ± 1%
EFCH4	flame	2.3 ± 43%	2.2 ± 44%	1.5 ± 23%	1.5 ± 59%	1.2 ± 90%	4.7 ± 29%
	smold	7.6 ± 22%	9.8 ± 38%	7.3 ± 10%	8.8 ± 13%	8.9 ± 13%	15.0 ± 15%
	fire	5.5 ± 36%	6.6 ± 13%	4.1 ± 13%	6.4 ± 29%	5.7 ± 32%	10.86 ± 9%
EFNMHC	flame	2.1 ± 44%	2.6 ± 42%	1.8 ± 28%	1.6 ± 60%	1.1 ±106%	4.1 ± 49%
	smold	4.2 ± 54%	7.0 ± 15%	4.8 ± 47%	6.6 ± 10%	6.1 ± 5%	10.1 ± 5%
	fire	3.6 ± 46%	5.4 ± 19%	3.2 ± 40%	4.9 ± 23%	4.0 ± 24%	7.6 ± 2%
EFPM	flame	12.34 ± 53%	11.5 ± 64%	9.4 ± 17%	11.0 ± 54%	5.7 ± 27%	11.3 ± 32%
	smold	17.49 ± 28%	19.0 ± 22%	24.3 ± 42%	16.8 ± 39%	12.5 ± 33%	22.1 ± 21%
	fire	14.78 ± 28%	18.7 ± 33%	19.8 ± 34%	14.5 ± 40%	10.2 ± 25%	18.2 ± 8%
EFPM25	flame	7.45 ± 67%	6.1 ± 69%	5.0 ± 59%	4.8 ± 24%	3.3 ± 29%	5.9 ± 27%
	smold	13.06 ± 18%	11.7 ± 20%	17.1 ± 39%	11.8 ± 33%	7.0 ± 20%	15.5 ± 10%
	fire	10.9 ± 34%	11.2 ± 29%	11.0 ± 29%	9.4 ± 34%	5.4 ± 4%	11.7 ± 5%

5.3.1.1 Total particulate matter.-- Total particulate matter emission factors (EF_{PM}) represent the ratio of the mass of particles produced to fuel consumed. The EF_{PM} values were always lowest for the flaming combustion phase and highest for the smoldering combustion phase, regardless of fuel type. Between fuel types, the lowest emission factors were measured for the tractor-piled conifer slash and highest for the eastside long-needled pine broadcast burn units during the smoldering combustion phase. Figure 5.3.1.1 illustrates these relative differences as a function of phase of combustion and fuel type for the average values presented in table 5.3.1. The fire average values presented in figure 5.3.1.1 were derived from the fuel consumption, as computed in section 5.3.2, and were weighted as described in section 4.3.5.

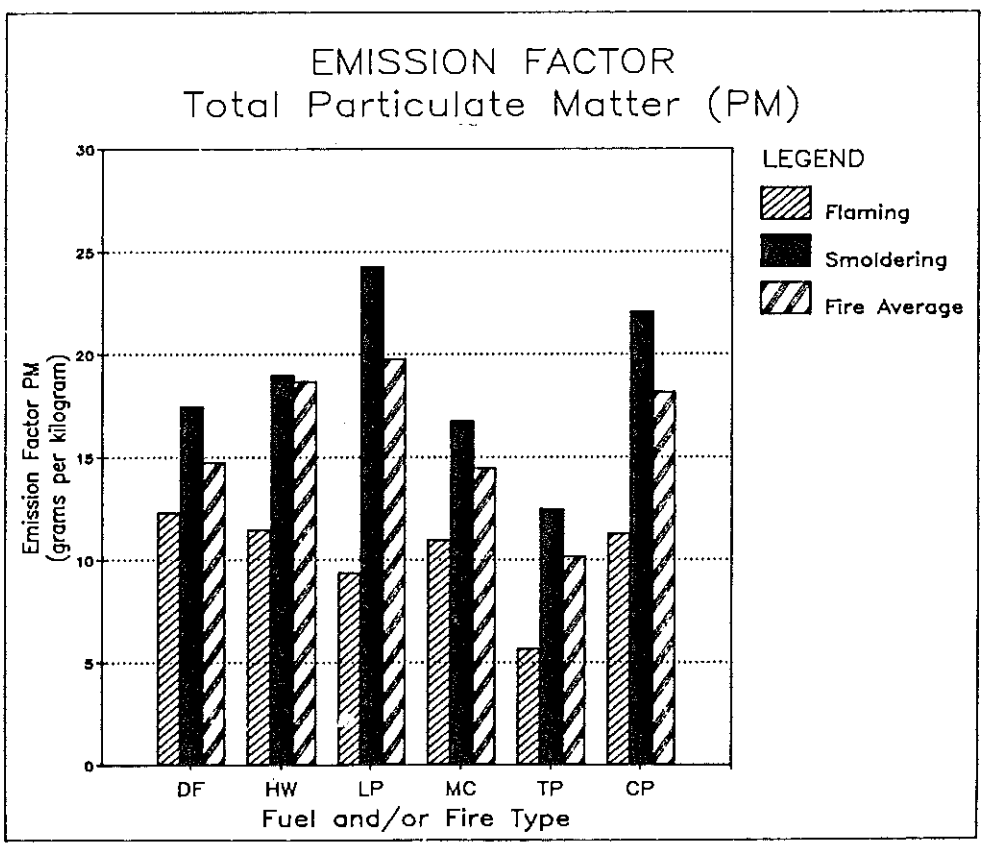


Figure 5.3.1.1. Emission factors for PM (EF_{PM}) illustrated for each fuel type by phase of combustion.

5.3.1.2 Particles < 2.5 micrometers.-- Particulate matter emission factors for particles less than 2.5 micrometers mean mass cutpoint diameter ($EF_{PM2.5}$) were generally lower than the EF_{PM} values. The data, illustrated in figure 5.3.1.2, are consistent with the EF_{PM} values in that the tractor-piled conifer slash $EF_{PM2.5}$ values are the lowest measured values for the flaming phase and the highest measured values occurred for the broadcast burns of long-needled conifer slash east of the Cascade Mountain Range.

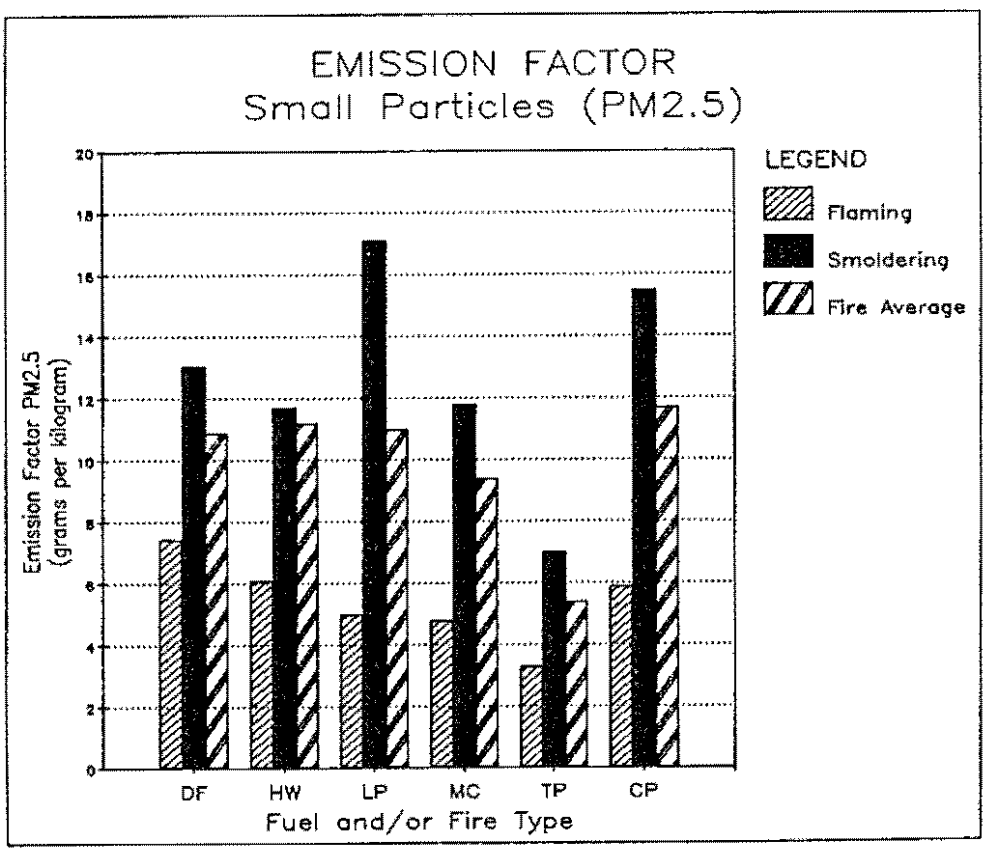


Figure 5.3.1.2. Emission factors for PM2.5 ($EF_{PM2.5}$) illustrated for each fuel type by phase of combustion.

5.3.1.3 Carbon dioxide.-- Figure 5.3.1.3 illustrates emission factors for carbon dioxide (EF_{CO2}), which range from 1401 for DF smoldering to 1746 for TP flaming. The EF_{CO2} values from tractor-piled fires were consistently higher than all other tests; DF tests were the lowest. The HW EF_{CO2} values were similar to DF.

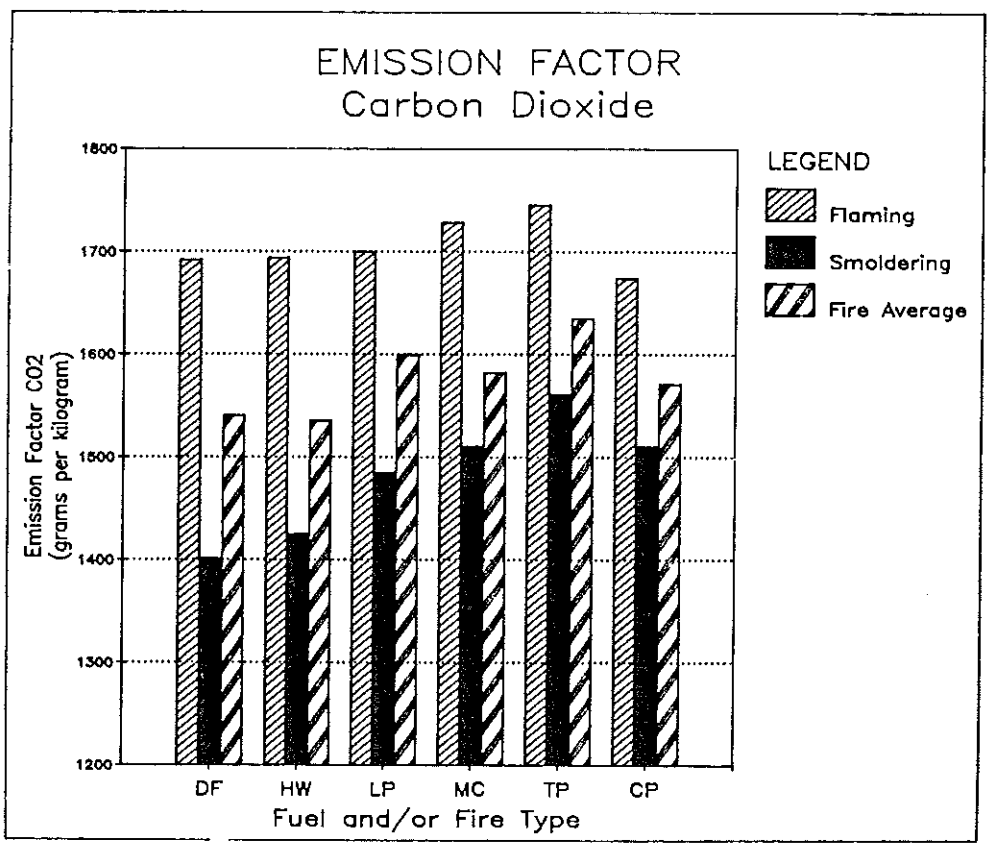


Figure 5.3.1.3. Emission factors for CO_2 (EF_{CO2}) illustrated for each fuel type by phase of combustion.

5.3.1.4 Carbon monoxide.-- The emission factors for carbon monixide (EF_{CO}) range from a low of 22.1 for TP combustion to values that are highest for the smoldering combustion phase for the DF units (231.5), as shown in figure 5.3.1.4.1. The combustion efficiency is lowest for the smoldering combustion phase of the Douglas-fir/western hemlock units and highest for the tractor-piled conifer slash (fig. 5.3.1.4.2). Combustion efficiency is highly correlated with carbon monoxide (fig. 5.3.1.4.3.)

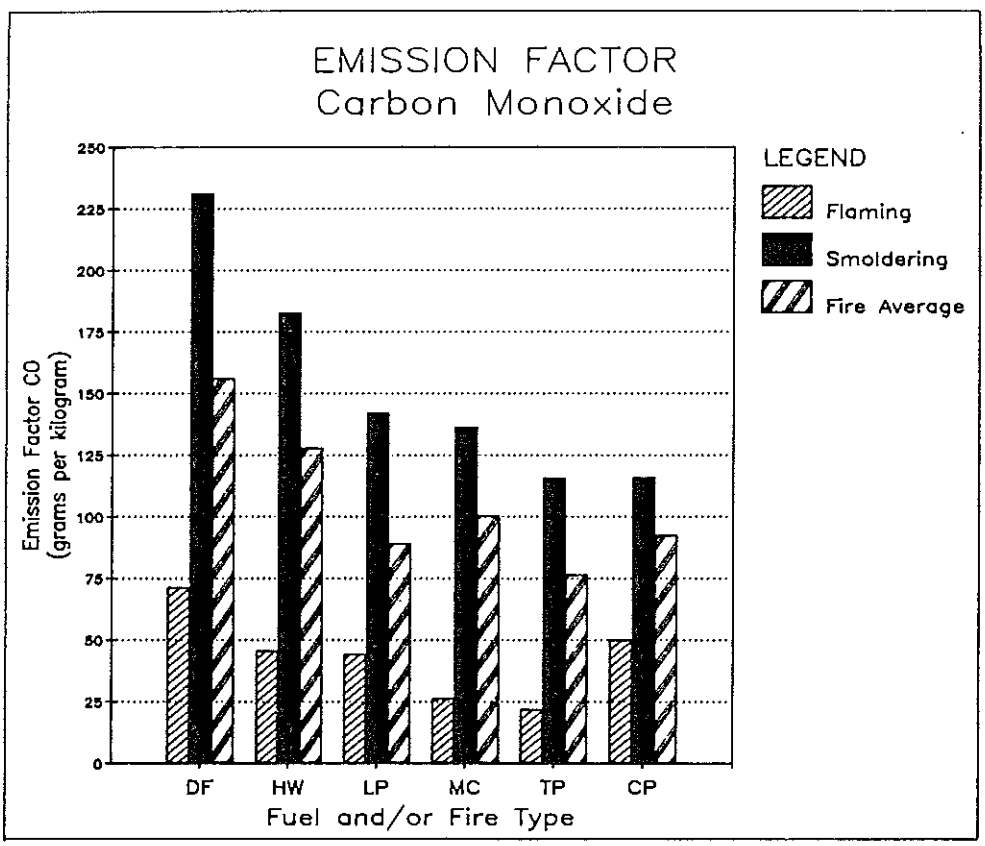


Figure 5.3.1.4.1. Emission factors for CO (EF_{CO}) illustrated for each fuel type by phase of combustion.

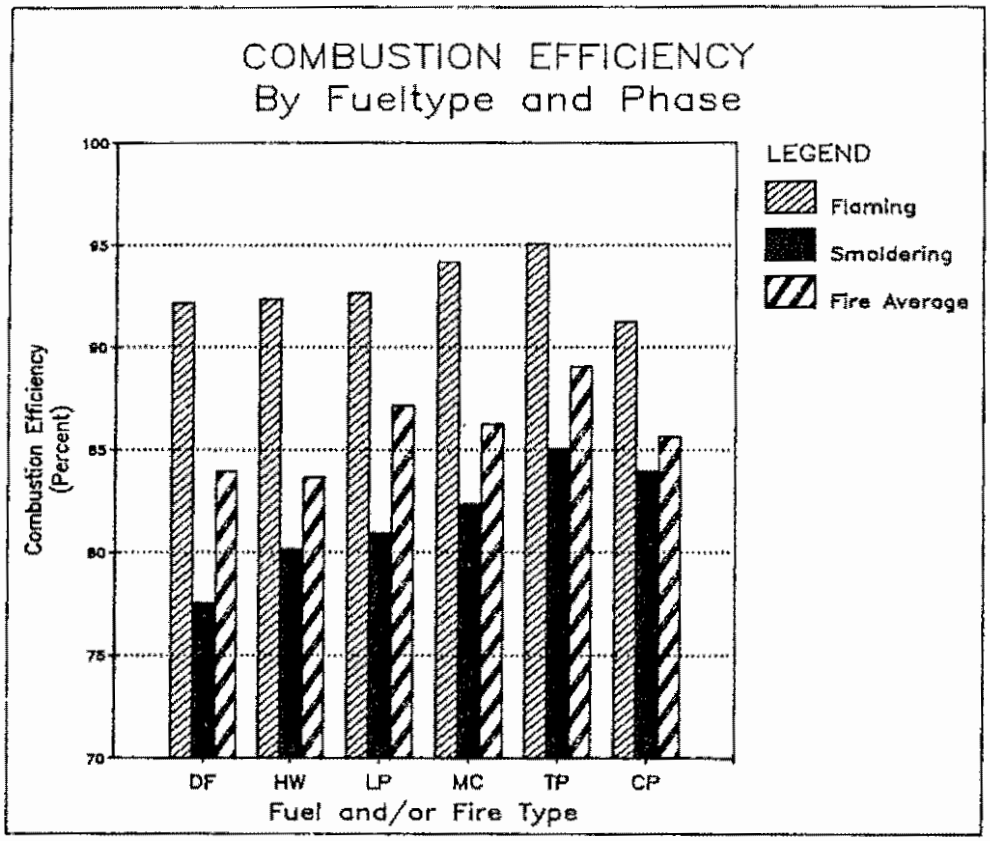


Figure 5.3.1.4.2. Combustion efficiency illustrated for each fuel type by phase of combustion.

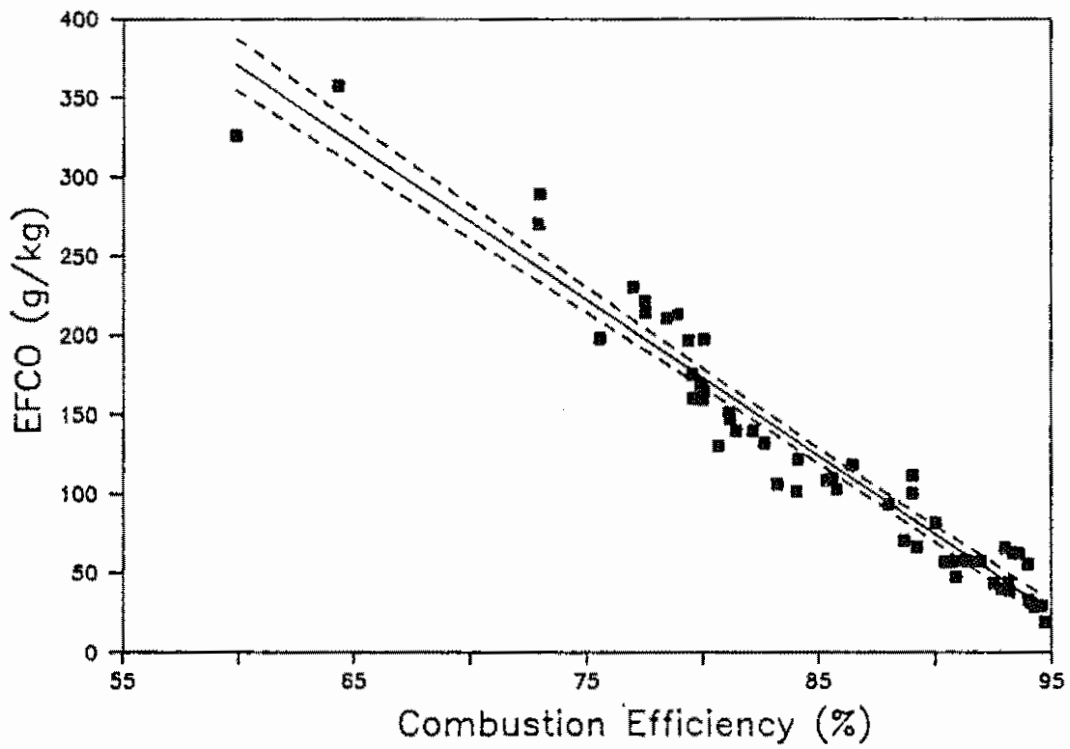


Figure 5.3.1.4.3. Plot of the strong relationship between combustion efficiency and EF_{CO}.

5.3.1.5 Methane hydrocarbons.-- Average emission factors for methane hydrocarbons (EF_{CH4}) ranged from 1.2 for the flaming TP tests to 15.0 for the smoldering CP tests. The CP tests produced the highest EF_{CH4} values for both combustion phases.

5.3.1.6 Nonmethane hydrocarbons.-- Emission factors for nonmethane hydrocarbons (EF_{NMHC}) on the average ranged from a low of 1.1 for tractor-piled burns for the flaming phase of combustion to a high of over 10 grams per kilogram of fuel consumed for the smoldering combustion phase tests of crane-piled materials.

5.3.2 Rate of Fuel Consumption

Fuel consumption was derived using three independent techniques: (1) inventory, (2) carbon flux, and (3) energy flux. The results from each of these techniques will be discussed.

5.3.2.1 Inventory methods.-- Field inventory methods were used as described in section 4.0, and the pre-burn fuel loadings for each test were presented in table 4.1.1. The results showed major differences in preburn fuel loading between westside and eastside units. Total fuel loading, which includes both woody and duff fuels ranged from a low of 8.63 kg/m^2 (38.5 tons/acre) to over 26.34 kg/m^2 (117.5 tons/acre). The range for eastside mixed-conifer stands was similar, but the range for long-needled pine stands was lower--3.8 kg/m^2 to 5.5 kg/m^2 (17.0 tons/acre to 24.5 tons/acre, respectively).

The field-inventoried (measured) consumption of the fuels is presented in table 5.3.2.1 for each test. Total fuel consumption ranged from 2.1 kg/m^2 (9.4 tons/acre) to 11.9

kg/m^2 (53 tons/acre), with the greatest consumption occurring on the westside units and the least on the eastside LP and MC units. The consumption is dependent on the moisture content of the 1000-hour fuels and on the abundance of fine fuels. The measured values for fuel consumption contained in table 5.3.2.1 have been used as a base to compare calculated values of the fuel consumption based on the carbon mass flux and energy flux methods. The comparisons, discussed later, will refer to the data in table 5.3.2.2.

Table 5.3.2.1. The field-inventoried (measured) fuel moistures and fuel consumption for each test.

Test name	Fuel complex	Date burned	Large wood fuel moisture	Measured fuel consumption		
				Flaming	Smoldering	Total
				(Kg/m2)		
GHA	HW	07/15/85	29%	6.0	5.6	11.7
EAA	HW	07/18/85	55%	3.6	3.9	7.6
VIC	HW	09/25/85	31%	6.2	1.0	7.3
CPC	HW	06/12/86	18%	9.0	2.9	11.9
LB1	HW	09/05/86	28%	7.2	4.7	11.9
LB2	HW	10/10/86	45%	2.0	0.6	2.6
LB3	HW	09/04/86	35%	7.4	2.0	9.5
LB4	HW	09/03/86	28%	8.1	1.5	9.6
LL1	LP	05/22/86	42%	1.3	0.9	2.2
LL2	LP	06/04/86	39%	1.5	0.6	2.1
CC1	LP	10/02/86	33%	3.0	0.6	3.6
CC2	LP	10/05/86	32%	4.2	0.3	4.5
RSP	MC	06/26/87	36%	3.7	1.6	5.3
WHH	MC	06/29/87	37%	4.9	3.3	8.2
HESS	MC	07/01/87	26%	2.2	3.0	5.2

5.3.2.2 Carbon-flux method.-- The carbon-flux method has been used for a number of years to estimate the fuel consumed in producing the measured emissions. Emission factor calculations, combustion efficiency, rate of energy release, and other calculated values based on fuel consumption are dependent on the measured carbon content of the gases and particles. It is a method that allows fuel consumption to be measured based on the release of carbon from the vegetative fuels and does not require the disturbance of the fuel bed. The technique as described under section 4.0 was used for the calculations.

The rate of fuel consumption over the duration of each of 22 tests (instrument malfunction precluded calculations for LL1) is illustrated by respective figures in Appendix D. The figures provide a means of assessing fuel consumption and the rate of energy release. An example is shown in figure 5.3.2.2.1 for Coles Corner 1 (CC1)--the test with the highest maximum rate of fuel consumption. The peak rate of fuel consumption was 24 $g/m^2/s$ during the flaming phase. This translates into an energy release rate of 360 kW/m^2.

For the Limestone Boulder units, the rate of fuel consumption ranged from a low of 1.9 $g/m^2/s$ to 18 $g/m^2/s$. These four units were in close proximity to each other but burned under extreme prescription conditions of very dry to very wet.

By integrating the area under the fuel consumption rate curves in figures Appendix D, the total fuel consumption was calculated by different increments of time for each combustion phase and was then summed for the entire fire (table 5.3.2.2). The results show fuel consumption for the flaming combustion phase to range from 6 percent to 75 percent of the total.

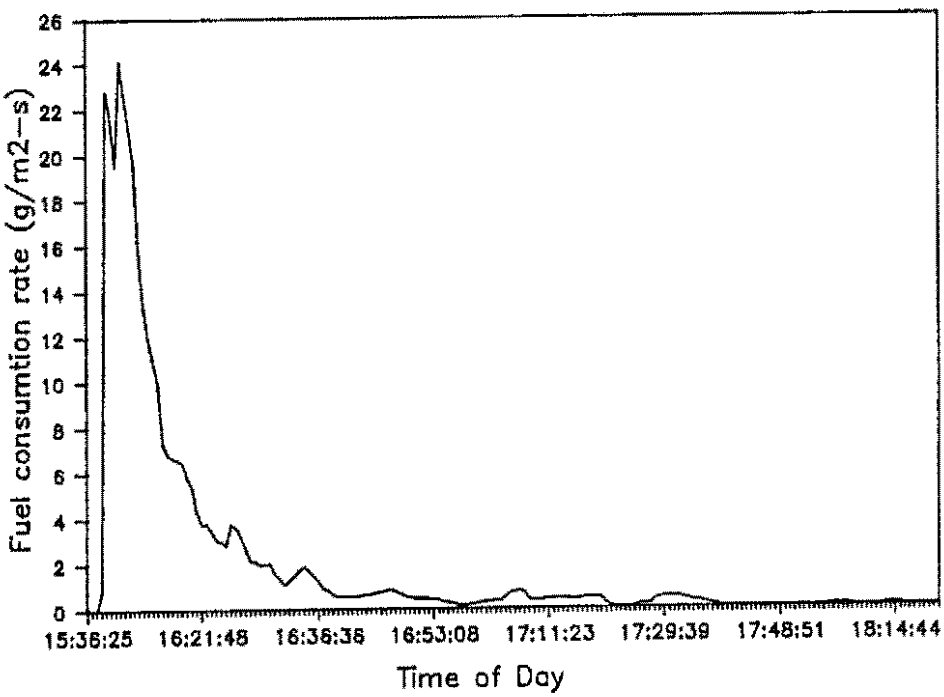


Figure 5.3.2.2.1. Plot of the rate of fuel consumption for CC1--the test with the highest maximum rate.

Figure 5.3.2.2.2 illustrates the flaming versus smoldering portions of total fuel consumption for three categories of broadcast-burned fuel types (HW, LP, MC). Fuel consumption is greater during the flaming combustion phase--percentagewise--for the ponderosa pine fuel type than for the mixed-conifer or westside hardwood fuel types.

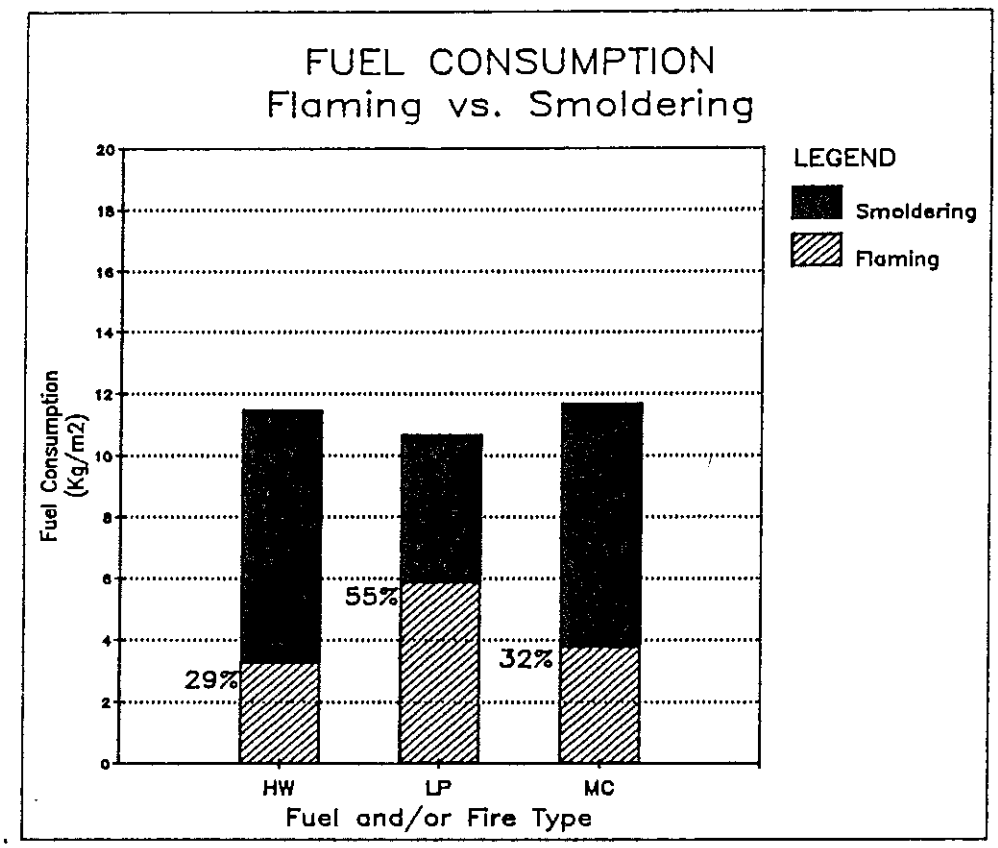


Figure 5.3.2.2.2. The flaming versus smoldering portions of total fuel consumption for three categories of broadcast-burned fuel types--HW, LP, MC.

The differences between the inventoried fuel consumption and that measured with the carbon flux technique are listed in table 5.3.2.2. For the hardwood fuel type, the carbon flux calculation of total fuel consumption averaged 19.8 percent higher than when measured by pre- and post-fire inventories. The GHA hardwood unit contained more rotten material of a larger diameter than any of the other tests, and the inventory technique apparently did not account for a large percentage of the rotten materials consumed by the fire. If GHA is ignored, the percent difference for the other 7 tests is 8.5 percent .

Table 5.3.2.2. Fuel consumption determined for each test by three methods--inventory, carbon flux, and energy flux. Averages are also shown for each fuel type.

Test name	Fuel Consumption: Inventory - Combustion phase F	S	Total	Carbon flux - Combustion phase F	S	Total	Energy flux - Combustion phase F	1st hour	Percent Difference: Carbon total vs inventory total	Energy flame vs carbon flame
	(Kg/m2)								(% difference)	
GHA	6.0	5.6	11.7	2.8	20.5	23.3	6.4	7.2	98.9%	129.4%
EAA	3.6	3.9	7.6	0.5	8.9	9.4	1.4	1.5	25.0%	176.9%
VIC	6.2	1.0	7.3	3.2	6.5	9.7	3.4	5.9	33.4%	5.0%
CPC	9.0	2.9	11.9	3.7	9.1	12.8	9.0	20.5	7.7%	142.9%
LB1	7.2	4.7	11.9	4.4	11.4	15.8	7.6	16.6	32.4%	72.2%
LB2	2.0	0.6	2.6	1.2	0.4	1.6	1.2	1.3	-40.3%	-2.5%
LB3	7.4	2.0	9.5	8.7	4.1	12.7	11.0	16.1	34.6%	26.8%
LB4	8.1	1.5	9.6	1.6	4.9	6.4	4.1	11.1	-33.2%	159.1%
Mean	6.2	2.8	9.0	3.3	8.2	11.5	5.5	10.0	19.8%	88.7%
LL1	1.3	0.9	2.2							
LL2	1.5	0.6	2.1	3.2	2.7	5.9	3.5	4.5	186.1%	8.7%
CC1	3.0	0.6	3.6	9.6	5.8	15.4	7.1	11.8	330.9%	-25.5%
CC2	4.2	0.3	4.5	5.0	6.0	10.9	4.2	8.9	144.0%	-16.3%
Mean	2.5	0.6	3.1	5.9	4.8	10.7	4.9	8.4	220.3%	-11.0%
RSP	3.7	1.6	5.3	5.7	6.2	11.9	5.3	8.7	125.3%	-6.9%
WHH	4.9	3.3	8.2	3.0	11.9	14.9	5.8	11.4	82.0%	92.6%
HESS	2.2	3.0	5.2	2.8	5.5	8.4	2.5	5.1	59.4%	-12.0%
Mean	3.6	2.6	6.2	3.8	7.9	11.7	4.5	8.4	88.9%	24.6%

For the six tests in conifer types on the eastside of the Cascade Mountains (combined long-needled pine and mixed conifer) the carbon flux technique averaged 154.6 percent greater fuel consumption than measured with the inventory method. Several factors may have contributed to this large apparent bias. First of all, no measurements of duff, litter, or crown needles were included in the inventory measurements of fuel consumption for the ponderosa pine units. Secondly, significant quantities of drift smoke occurred on both of the Coles Corner units which would have increased the measured concentration of carbon released on a unit area basis. A considerable quantity of large-diameter rotten material was contained on the three mixed-conifer units on the eastside.

5.3.2.3 Energy balance method.-- The thermal properties of the gases in the convection column, as evaluated at the locations of the sample packages, were used in estimating the quantity of heat released and the calculated quantity of forest fuel consumed to produce the measured heat for the flaming phase only of the test fires. To measure small differences in temperature such as occur during the diedown phase or smoldering combustion phase of the fire would require a much larger grid of temperature sensors. These sensors would be used to measure the temperature of the precombustion air entering into the burn area.

Because of the difficulty in measuring the temperature of the precombustion air, it was decided to compute only the energy flow during the period of time with the greatest difference in temperature. A period of 1 hour was selected for this calculation. It was further reduced to a comparison of the fuel consumption during the flaming phase as computed using the carbon flux and energy flux techniques. No corrections have been made for radiation losses, conduction into the soil, heat of condensation of the water vapor, temperature measurement errors, or combustion efficiency. The heat content of the fuel was assumed to be constant for all fires-- 15.1 MJ/kg.

The results shown in table 5.3.2.2 display significant departures for the hardwood units and much lower differences for the eastside Cascade units. These departures may be due to differences in (1) the carbon content of the forest fuel consumed, (2) combustion efficiency, and/or (3) heat content of the fuels.

5.3.3 Rate of Energy Release

The rate of energy release was computed by multiplying the rate of fuel consumption by the heat content of the fuel

(15.1 MJ/kg). Rate of energy release is closely coupled to combustion efficiency, and the emissions produced are correlated with both rate of energy release and combustion efficiency. Average rates of energy release (labelled "heat rate") are shown in the tables in Appendix C for each test, for each of the phases of combustion.

Table 5.3.3 is a summary of average rates of heat release (I_R) for each fuel type by phase of combustion. Note the differences between the piled slash tests (TP, CP) and the broadcast burns. Flaming phase I_R is a factor of two greater for both piled slash types than for the others; smoldering values are at least threee times greater. The relatively high I_R for flaming phase LP is the result of an extremely high value of 234.3 for the CC1 test. With that observation removed, the mean for flaming phase LP is 66.3--quite similar to the other values for broadcast burns.

Table 5.3.3 Average, minimum, and maximum values of heat release rate (I_R) for the six fuel types, by combustion phase.

Fuel type	Phase	Rate of Heat Release (I_R) Mean	Minimum	Maximum
		(Kw/m2)		
DF	F	62.1	15.2	155.8
DF	S	12.9	1.7	38.5
HW	F	54.5	6.7	118.7
HW	S	18.0	1.0	49.7
LP	F	126.0	54.7	234.3
LP	S	10.4	8.6	11.6
MC	F	62.5	42.9	84.7
MC	S	19.2	9.0	29.1
TP	F	128.8	30.0	202.2
TP	S	44.7	5.4	67.3
CP	F	143.9	26.0	286.9
CP	S	95.6	80.9	110.3

Rate of fuel consumption is correlated directly with rate of heat release for the calculated values in Appendix C. In other words, no correction has been applied for the effect of combustion efficiency on heat release or other heat loss transfer processes. Hence, by multiplying values represented by the figures in Appendix D by 15.1 MJ/kg, the rate of energy release in kW/m^2 can be computed.

6.0 DISCUSSION

A strategic objective of the research presented in this report was stated in section 3.0, objective number five:

> "To compare these measurements and models with those already developed for broadcast burning of coniferous logging slash...".

Previous research in the coniferous logging slash fuel types west of the Cascade Mountain Range in Washington and Oregon was described by Ward and Hardy (1986). In that document, relationships between variables and differences in variables between combustion phases were discussed and presented. With the addition of twenty three tests from the present research, the "strength" of some of these relationships is more apparent. Also, it is now possible to provide a comparison of variables between the six fuel types studied.

The following sections provide a discussion of homogeneity of variance, a comparison of means, presentation of significant relationships, and the derivation and results of new modeling efforts.[4]

6.1 Homogeneity of Variances

Multiple comparison tests invoke conservative criteria for determining the significance of differences between means. However, these tests assume that the populations from which samples are taken are normal and display homogeneity of variance. Inequality of sample size is of particular concern with respect to homogeneity of variance(s). The data presented here exhibit widely varying sample sizes (n) between fuel types: twelve tests in DF; eight HW; four LP;

---

[4]The statistical and information system SPSS/PC+ (Norusis/SPSS Inc. 1988) was utilized in the statistical evaluations discussed in section 6.

three MC; four TP; and four CP. Another obvious antagonist to the statistical procedures is the relatively small sample size of several of the fuel types. Additional factors introducing variance in the sample sizes were sampling malfunctions and measurement artifacts causing necessary reductions in the sample size for certain variables for certain tests.

Tests for homogeneity of variances were performed to first ensure that the required hypothesis that the populations have the same variance could not be rejected. These tests included Cochran's C, the Bartlett-Box F, and Hartley's F Max. Only the means of variables exhibiting both normality and homogeneity of variance were subsequently compared for significance of difference(s).

6.2 Multiple Comparisons of Means

All differences between means discussed in this section are illustrated by respective diagrams in Appendix E, where means are shown, by fuel type, for a number of emission variables. The diagrams are grouped by three fuel type categories: (1) all fuel types [E.1], (2) broadcast burn fuel types [E.2], and (3) three composited fuel types--hardwoods, conifers, and piles [E.3]. Within each fuel category, the means are sub-grouped by phase of combustion.

In each diagram (one per variable per phase), all fuel types with **similar** means are underlined. Conversely, it can be interpreted that fuel types **not** sharing an underline have significantly different means (at the .05 level) for the repective variable. Note in the diagrams that, for each variable, the fuel type abbreviation is followed by the number of observations (n); beneath these are the means.

For example, the diagram for EF_{CO2}, all fuels, flaming phase (E.1.1) is:

EF_{CO2}	CP-4	DF-1	HW-8	LP-3	MC-3	TP-4
	1674	1692	1694	1700	1728	1745

Here, the only means with a significant difference are CP (n=4, mean=1674) and TP (n=4, mean=1745). All other groupings of means are similar at the .05 level.

The relative differences between the means for emission factors can also be seen in the bar-graph figures in section 5.3.1.

6.2.1 Differences Between Means--All Fuel Types

a. EF_{CO2}.--The example above described the difference in EF_{CO2} between CP and TP for the flaming phase. For the smoldering phase and for the total fire, EF_{CO2} for TP is different than for both DF and HW.

b. EF_{CO}.--Flaming phase EF_{CO} for DF is different than for MC and TP. For the smoldering phase, DF is different than all other fuel types; the others are all similar.

c. I_R.--While it was expected that I_R (reaction intensity) would differ significantly between the piled-slash tests and the other tests, the only observed difference during the flaming phase was between CP(143.9) and HW(54.5) However, for the smoldering phase, CP was higher than all others and TP was different than all except MC.

d. EF_{PM}.--The variances for the flaming phase EF_{PM} differed too much between fuel types to allow a comparison of means. The only identifiable difference

was between TP and LP for the smoldering phase.

e. TC.--To generalize differences in means for TC, DF was different than LP and MC, regardless of combustion phase. MC was different than all others for the flaming phase, while similarity existed between CP, HW, and LP, regardless of phase.

It was expected that means for many of the variables would differ significantly between the piled-slash tests and the other fuel types. For most of the variables discussed above in section 6.2.1, means for either or both of CP and/or TP were shown to be different than the means of the other fuel types. Gross differences in fuel distribution, fuel arrangement, and ignition propagation exist between the piled-slash tests and the broadcast burns. These differences explain much of the difference in fire behavior and subsequent emission characteristics.

By considering only the broadcast burn tests (DF, HW, LP, and MC) differences more directly (possibly) related to fuel parameters may be discussed.

6.2.2 Differences Between Means--Broadcast Burns

a. EF_{CO}.--The mean EF_{CO} for DF was significantly different than for HW and MC. Conversely, DF was similar to LP, and similarity existed between MC, LP, and HW. For the smoldering phase and for the total fire, DF was different than MC and LP. Means were similar for LP, MC, and HW.

b. EC.--Elemental (graphitic) carbon for flaming phase MC was different than either HW or LP. For the smoldering phase, MC was different than DF and LP. For either phase, HW, DF, and LP were similar.

c. $EF_{PM2.5}$.--Means for $EF_{PM2.5}$ can only be compared for the smoldering phase, where LP was different than HW. All other combinations of fuel types were similar.

6.2.3 Differences Between Means--Three Groups

The general fuel type groups described in this section have been composited from all fuel types, and include hardwoods (HW), all conifers (CO), and the piled slash (PI). Few data with homogenous variances were available after this compositing. Variables remaining for analysis included I_R, EF_{CO2}, EC, Combustion efficiency, and EF_{CH4}:

For both phases of combustion, all piled-slash means except EC were different than hardwood and conifer; hardwood and conifer were similar in all cases except for EC. For EC, smoldering phase, the only difference was between piled-slash and conifers; hardwood was similar to both conifer and piled-slash.

6.3 Relations Between Combustion Products

Within the total data set, numerous relationships exist between variables and between groups of variables. Certain calculated variables are clearly dependent on the observations upon which they were derived. For example, EF_{CO2} and combustion efficiencyare both derived (in part) from CO_2 concentrations. Howver, many linear associations exist between primary combustion products, trace emissions, and emission factors. These relationships were determined by generating correlation matrices for various combinations of combustion phase and fuel type.

Presented in Appendix F are correlation matrices for two groupings of data. The first group includes all tests, and the second group includes only the broadcast burn tests--piled-slash tests were excluded. Four strata are presented for each group: (1) flaming phase, (2) smoldering phase, (3) flaming and smoldering phase, and (4) fire average data. The third strata, flaming and smoldering, is basically all of the observed data for the test. By simply aggregating the data from the two phases rather than using the fire-averaged data, the data is a true representation of the combustion conditions rather than an average. The data within this third strata form the primary basis for the evaluations discussed in this section.

The matrices have been generated by linear regression analyses. The values within each matrix are regression coefficients (r), calculated on the basis of two-tailed probabilities. A single asterisk or double asterisk is used in Appendix F to indicate significance at the 90 and 95 percent level of confidence, respectively.

The algorithms describing linear associations for 17 pairs of variables can be derived from the data in table 6.3.1. The first group of data in table 6.3.1 are for the total data set (all tests), followed by the second group comprising only the broadcast burn data (piled slash excluded). The x-coefficient and constant represent the slope (a) and y-intercept (b), respectively, in the linear equation $y = a + bx$, where a value can be predicted for y based on an observed (or calculated) x. The number of observations and coefficients of determination (R^2) are also shown.

It should be noted that correlation does not necessarily imply causation. While certain variables are highly correlated, they are also highly correlated with other

variables. Nevertheless, the relationships shown here demonstrate progress towards development of parametric models for the prediction of emissions production from prescribed burning.

The figures presented at the end of sections 6.3.1 and 6.3.2 sections are scatter plots with regression equations fitted (least squares fit) to the data. Upper and lower confidence intervals shown represent the .95 level.

Table 6.3.1 Linear regression equations for variables from the total data set and from only the broadcast burn data.

Regression Variables		Linear Equations			
Dependent	Independent	X-coeff.	Constant	Number Obsv.	R^2
All Tests					
[PM]	[PM2.5]	0.55545	0.332	57	0.835
[CO]	[PM]	0.12430	3.083	60	0.634
[CO]	[PM2.5]	0.07713	1.405	57	0.735
[CO]	[CH4]	0.05917	1.256	61	0.773
[CO]	[NMHC]	0.01681	0.474	61	0.623
[CH4]	[NMHC]	0.28821	0.095	61	0.329
[CH4]	[PM2.5]	1.06680	1.348	57	0.539
EFPM	EFPM2.5	0.58116	0.668	56	0.845
Cmbst. Effcy.	EFCH4	-0.43183	42.711	59	0.765
Cmbst. Effcy.	EFCO	-9.84351	960.598	63	0.947
Cmbst. Effcy.	EFPM2.5	-0.63518	64.348	57	0.693
Cmbst. Effcy.	EFPM	-0.64327	69.759	58	0.525
Broadcast Burns					
IR	Trace Elements	0.01893	3.003	26	0.090
IR	Sum (S, Cl, K)	0.02080	1.299	43	0.217
IR	Elemental Carbon	0.10159	5.533	35	0.219
IR	EFPM2.5	-0.06308	12.558	40	0.308
IR	(EFPM-EFPM2.5)/EFPM2.5	0.00582	0.665	39	0.082

Variables in brackets, eg. [PM], are concentrations.

6.3.1 Correlation(s) of Total Data Set

Certain fuel and combustion parameters are highly variable in consideration of the total data set. This is due primarily to gross differences in fuel distribution and arrangement in the piled slash types. The associations between several primary combustion products are nevertheless of interest.

6.3.1.1 Concentrations of PM and PM2.5.-- It is expected that the concentration of total particulate matter (PM) is linearly correlated with the concentration of fine particulates (PM2.5). The relationship shown in figure 6.3.1.1 has a slope of 0.56. That is, for each 1 ppm increment in PM, the algorithm predicts an increment of 0.56 ppm PM2.5. The relationship is quite strong (R^2=.835).

6.3.1.2 CH_4 and NMHC concentrations.-- The relationship between concentrations of CH_4 and NMHC is illustrated in figure 6.3.1.2. The model predicts a .28 ppm change in NMHC for each change of 1.0 ppm CH4 concentration; R^2 is .33.

6.3.1.3 EF_{PM} and $EF_{PM2.5}$.-- The relationship between emission factors for PM and PM2.5 is quite similar (although stronger) to that for concentrations of the two parameters (6.3.1.1). Increased strength as well as confidence is gained through the calculation of emission factors which accounts for the amount of (and, hence, the variance in) the fuel consumed during production of the emissions. Figure 6.3.1.3 shows the linear association between EF_{PM} and $EF_{PM2.5}$.

6.3.1.4 Combustion efficiency and EF_{CO}.-- If combustion efficiency were equal to 1.0, then all of the carbon from the fuels would be converted to CO_2. If the fuel undergoes incomplete combustion (as it does), a portion of the carbon

would be converted to other combustion products; for example, carbon monoxide. Figure 6.3.1.4 illustrates the strong correlation between combustion efficiency and EF_{CO}, where EF_{CO} increseas by nearly 200 g/Kg when combustion efficiency decreases by 20%.

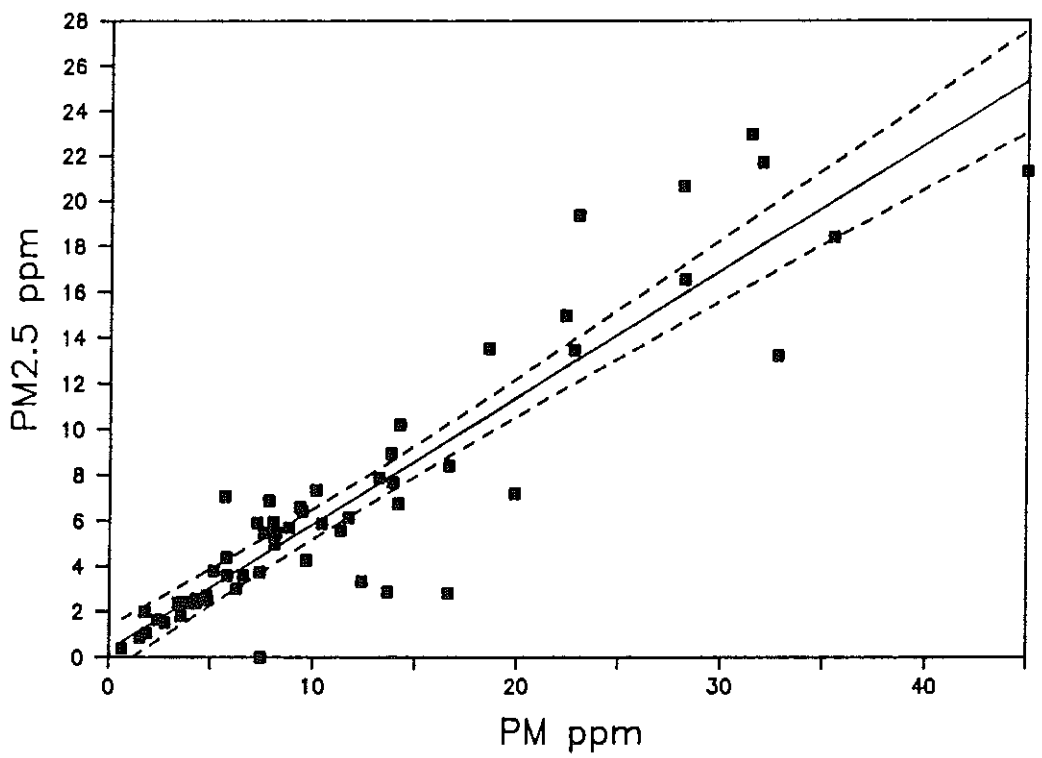


Figure 6.3.1.1 Linear association between concentrations of PM and PM2.5. The regression line is plotted with 95% confidence intervals.

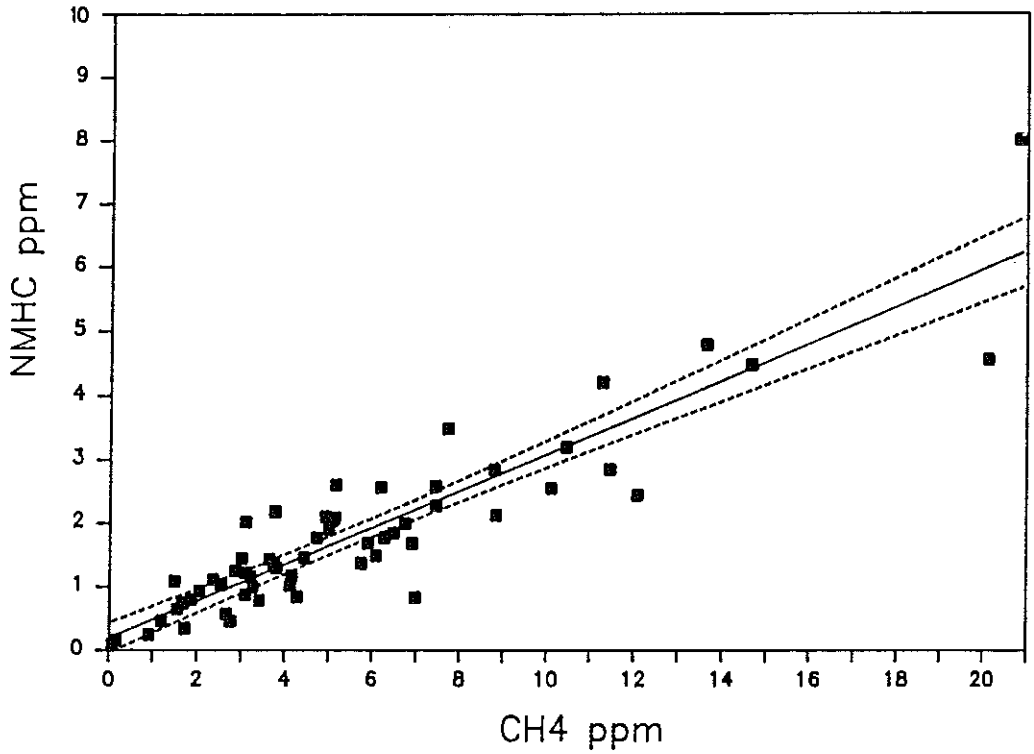


Figure 6.3.1.2 Linear association between concentrations of CH_4 and NMHC. The regression line is plotted with 95% confidence intervals.

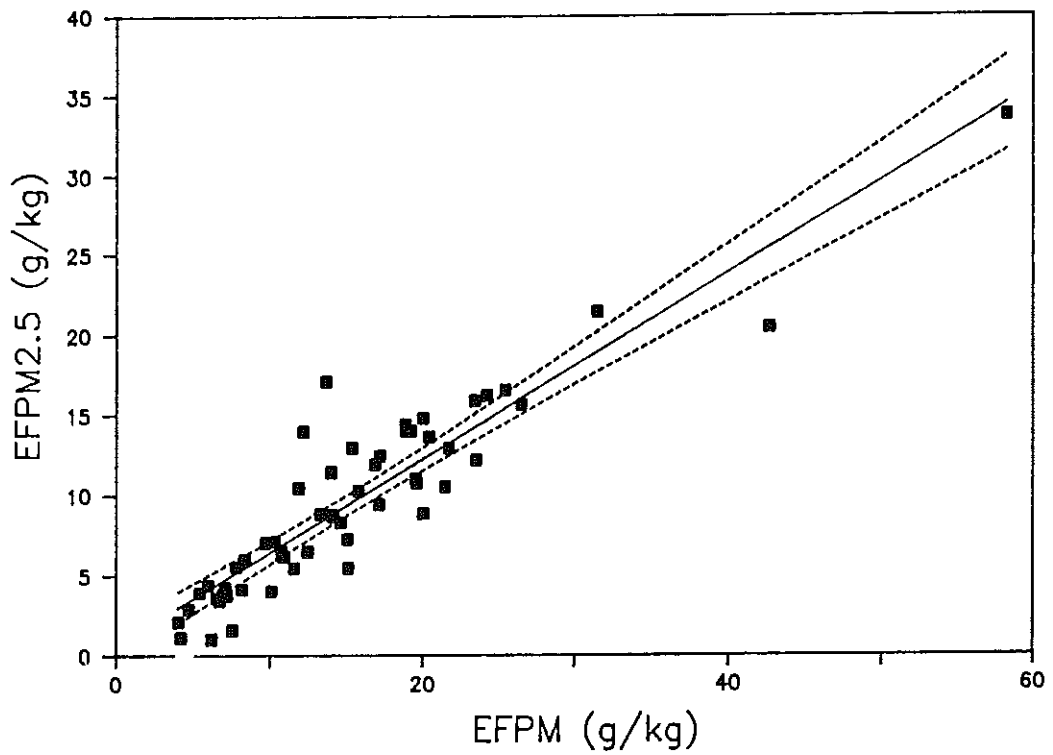


Figure 6.3.1.3 Linear association between EF_{PM} and $EF_{PM2.5}$. The regression line is plotted with 95% confidence intervals.

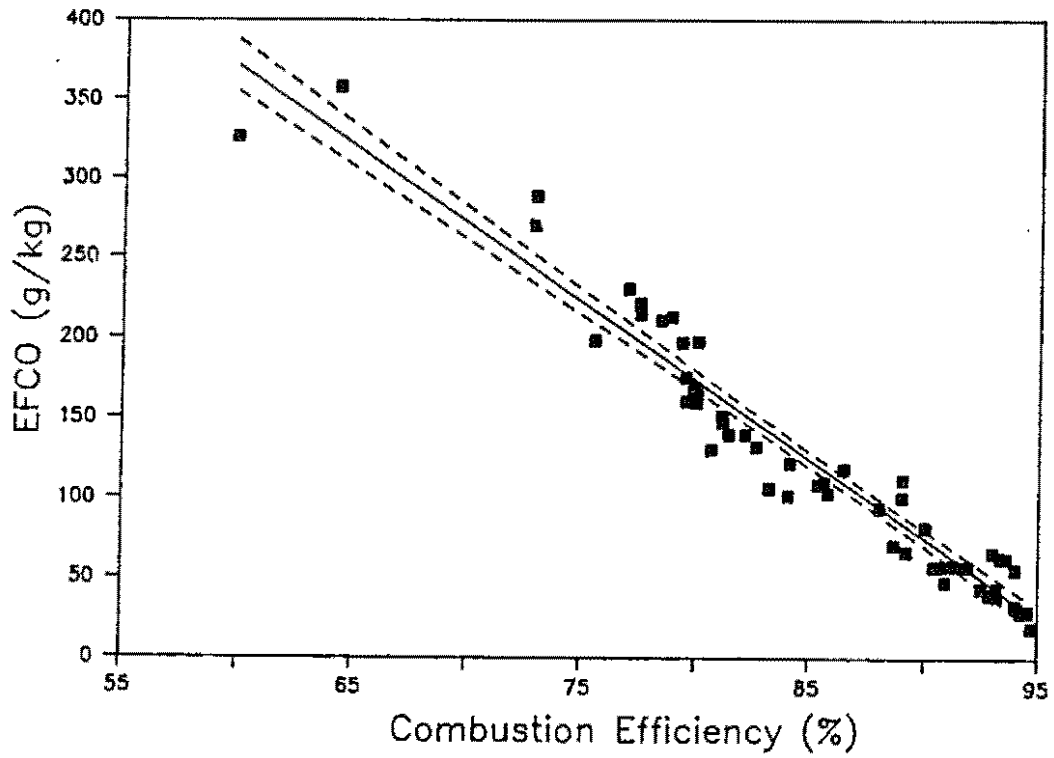


Figure 6.3.1.4 Linear association between combustion efficiency and EF_{CO}. The regression line is plotted with 95% confidence intervals.

6.3.2 Correlations(s) Within Broadcast Burn Data

Reaction intensity (I_R) appears to be a significant dependent variable in consideration of several primary combustion products. However, it has been shown in section 5.3.3 that large differences in I_R exist between the broadcast burns and the piled slash tests; piled slash tests had I_R values 2-5 times higher than the broadcast burn values (table 5.3.3). The differences are coincident with significant differences in other independent variables such as fuel distribution, fuel arrangement, and ignition propagation. This section is therefore limited to consideration of only the data from the broadcast burn tests.

The strength of the correlations of variables with I_R has been diminished by two extremely high observations of I_R.

The two values (shown in table 5.3.3) are: 155.8 for WCB2, flaming, phase; and 234.3 for CC1, flaming phase. While these values are statistical outliers, evidence was not available to support their exclusion. However, it is reasonable to consider the improvements their exclusion could make to the associations illustrated by the figures presented in the next sections.

6.3.2.1 I_R and total trace elements.-- A very slight trend between I_R and the sum of all trace elements (expressed as percent of PM2.5) is shown in figure 6.3.2.1. The trace element content of the PM2.5 seems to increase with increases in I_R. The outlying I_R value of 234.3 clearly has an effect on the regression.

6.3.2.2 I_R and the sum of S, CL, and K.-- The association between I_R and the percent of PM2.5 that is S, CL, and K is poorly developed. As illustrated in figure 6.3.2.2, the variance in the sum of S, Cl, and K is extremely high, and I_R outliers tend to "flatten" the regression line.

6.3.2.3 I_R and elemental carbon.-- Elemental carbon exhibits a slight dependence on I_R. Figure 6.3.2.3 shows the scatter in elemental carbon, and illustrates the effect on the regression of the I_R values greater than 140 kW/m2.

6.3.2.4 I_R and $EF_{PM2.5}$.-- It was hoped that a predictive algorithm could be developed for $EF_{PM2.5}$. Linear regression analysis applied to broadcast burn data gives a coefficient of determination of .31 for the association between I_R and $EF_{PM2.5}$. The data are plotted in figure 6.3.2.4, where a negative relationship is shown. Note the high I_R observation.

6.3.2.5 I_R and the EF_{PM}-to-$EF_{PM2.5}$ ratio.-- The difference between EF_{PM} and $EF_{PM2.5}$ can be expressed by the equation $(EF_{PM}-EF_{PM2.5})/EF_{PM2.5}$. The differences are plotted as a function of I_R in figure 6.3.2.5. The size distribution of the particles is affected by heat release rate (I_R), where the number concentration of particles shifts toward the larger diameters for fires of higher intensity. Ward and Hardy (1986) have previously described this relationship. The largest differences between EF_{PM} and $EF_{PM2.5}$ tend to occur whre I_R is the greatest, and is thought to be caused by increased mechanical disturbance and turbulence entraining large ash particles in the combustion plume.

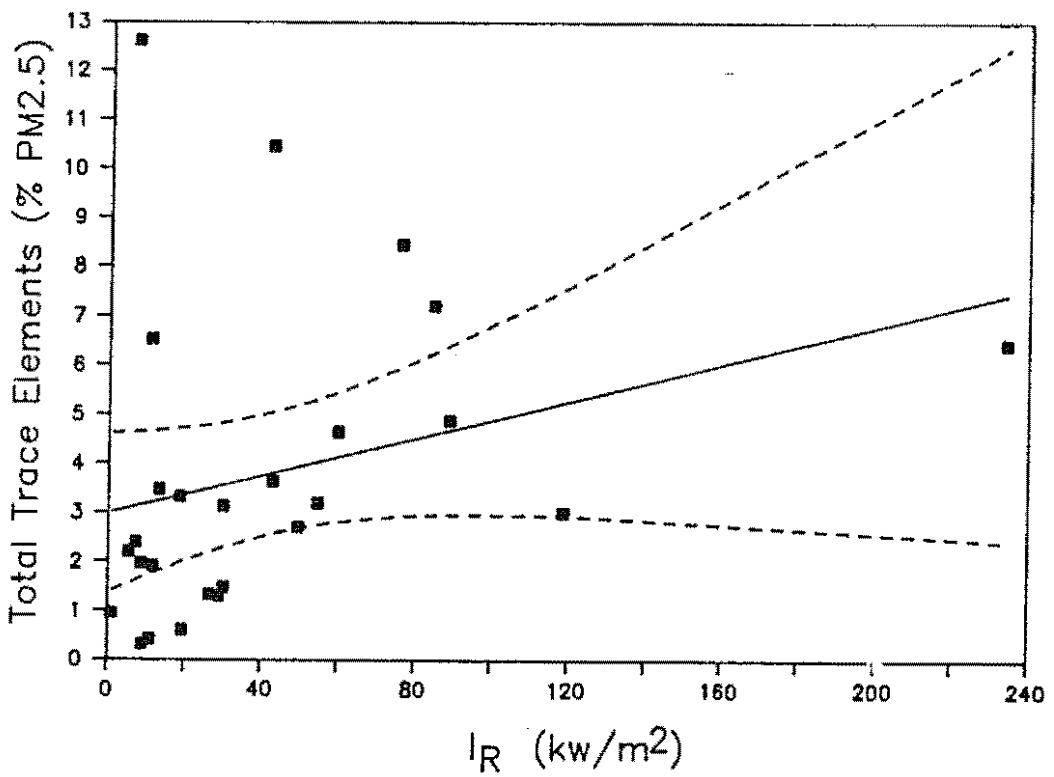


Figure 6.3.2.1 Linear association between I_R and the sum of all trace elements (as percent of PM2.5). The regression line is plotted with 95% confidence intervals.

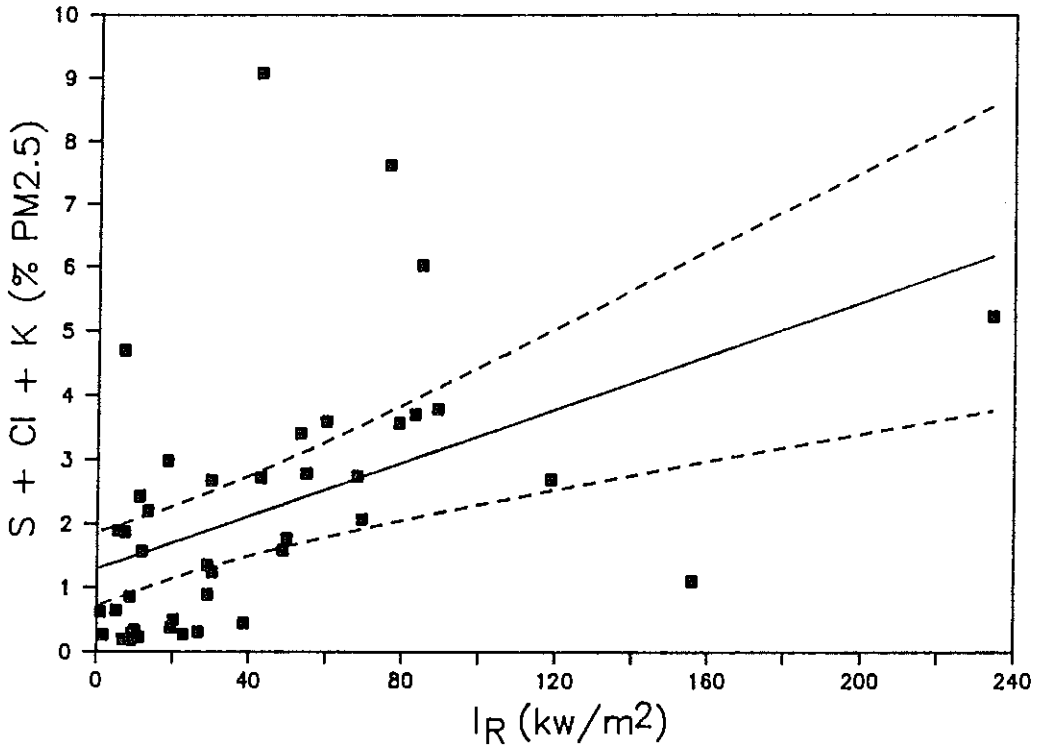


Figure 6.3.2.2 Linear association between I_R and the sum of the trace elements S, Cl, and K (as percent of PM2.5). The regression line is plotted with 95% confidence intervals.

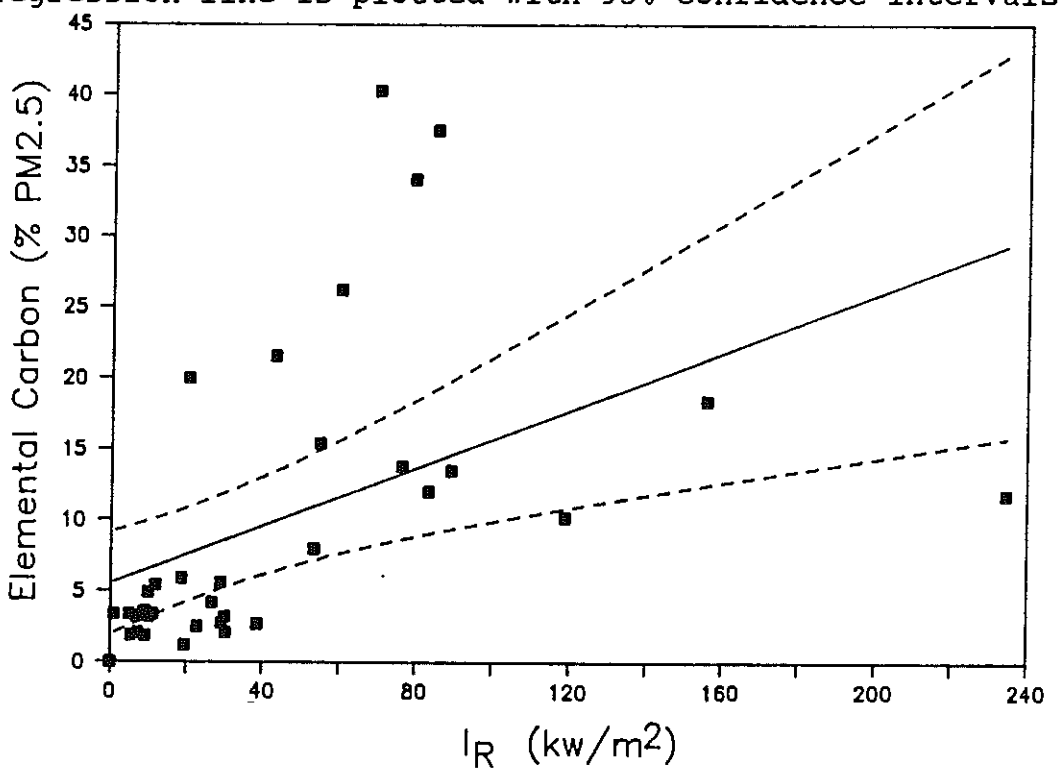


Figure 6.3.2.3 Linear association between I_R and elemental (graphitic) carbon (as percent of PM2.5). The regression line is plotted with 95% confidence intervals.

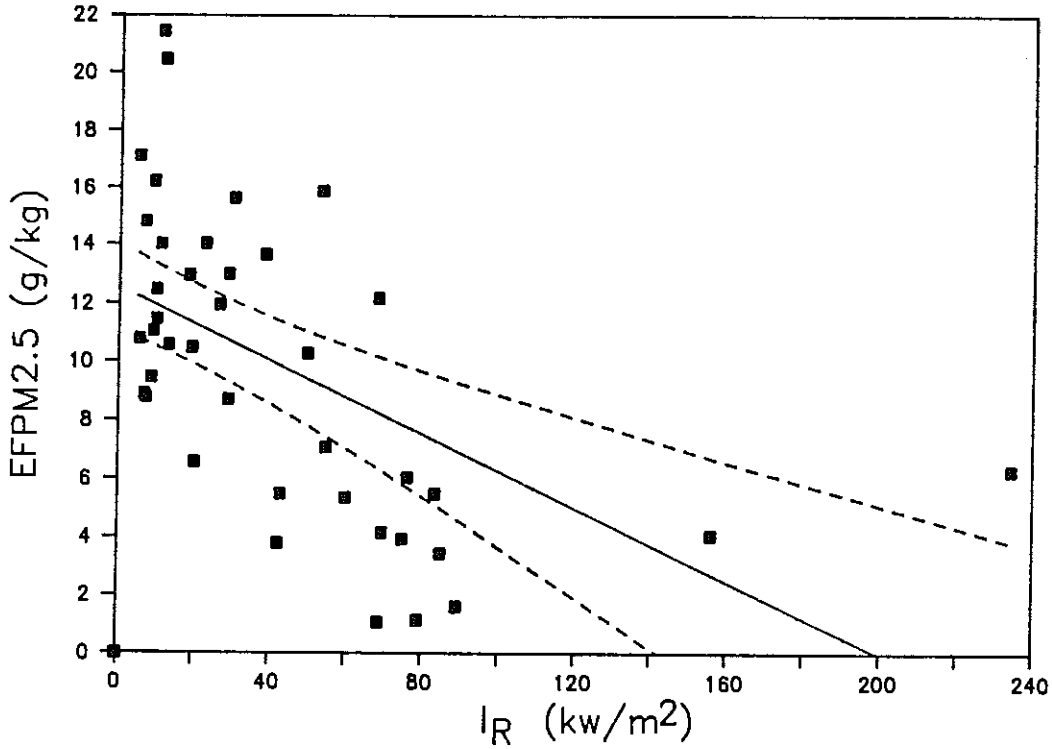


Figure 6.3.2.4 Linear association between I_R and $EF_{PM2.5}$. The regression line is plotted with 95% confidence intervals.

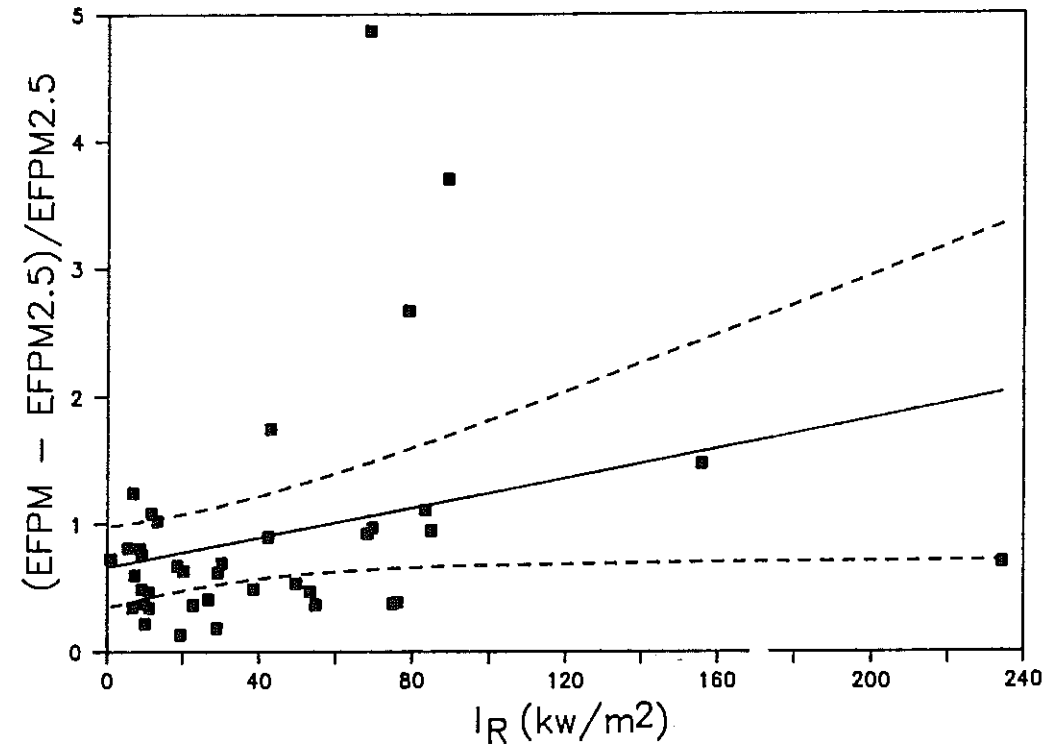


Figure 6.3.2.5 Linear association between I_R and the difference between EF_{PM} and $EF_{PM2.5}$. The regression line is plotted with 95% confidence intervals.

6.4 Modeling of Fuel Consumption

Methods are needed for predicting the rate of fuel consumption as a function of time, fuel, and weather variables. A model for describing fuel consumption as a function of time would be valuable in assessing source strength as a function of fuel and weather variables. The variation in the rate of fuel consumption over time is the most important variable to characterize for assessing source strength. Local smoke impacts and dispersion processes are strongly dependent on the rate of energy release and source strength of the fire.

Several approaches have been tried to develop mathematical equations that fit the observed rates of fuel consumption for the broadcast prescribed fires. Several units of Douglas-fir/western hemlock were studied during 1983 and 1984. The results were used to develop a discontinuous set of functions describing the rate of increase and decrease in fuel consumption as a function of the maximum rate of consumption (thought to be partially predictable based on the abundance and distribution of fine fuels) and on a time decay constant.

6.4.1 1984 Source Strength Model and What it Showed

The modeling work done by Ward and Hardy (1984) was based on empirical data collected from the Douglas-fir/western hemlock prescribed fires. The measurements of fuel consumption over time from undisturbed fuel beds was a pioneering effort to characterize the maximum rate of consumption of biomass fuels and the rate of diedown of fires through to the point of extinction. The exponential decay modeling effort defined a time constant which was used to define the decreased source strength for the release of heat and emissions over time on a unit area basis. The

results of this work have been used in defining the effect of changing management practices on emissions production. Several interesting findings have resulted: independent duff consumption on very dry units continues to produce a major quantity of emissions over many hours, whereas, units that are burned while duff is still moist tend to have emission production strength profiles that decrease rapidly to extinction immediatley following the consumption of the fine fuels. In the following section of this report, we discuss a new effort to fit mathematical expressions to the rate of consumption and rate of energy release for large number of prescribed burns done in different species composition and burned under different weather influences. The goal is to assist fire managers in developing prescriptions that can further reduce the quantity of smoke from prescribed burning operations.

6.4.2 New Efforts--Modeling By Parts

The slash burn is broken into two phases--flaming and smoldering. Some of the quantities needing definition are listed below:

t = time in hours from the start of the fire.
tf = time in hours to the end of the flaming phase.
y = the amount of fuel consumed by time t per unit area.
c = total amount of fuel available for burning per unit area.
y = y/c = the relative amount of fuel consumed by time t.
Alpha = the value of Y at time tf.
Beta = dY/dt at time tf.

The smoldering phase will be modeled first.

6.4.2.1 Smoldering phase.-- Approximately a straight line can be obtained by plotting the actual fuel consumption using the relationship t and ln (1-y/c). This leads one to the relationship ln(1-Y) = a-bt or, equivalently, Y=1-exp(-bt+a). Alternatively, assuming the rate of consumption of fuel is proportional to the amount of available fuel, the differentiable equation dY/dt=b(1-Y) is ln(1-Y)=bt-a where -a is the constant of integration. This is clearly the same result as before. From this, it follows that dY/dt=b*exp(-b*t+a).

The constants a and b can be described. At t=tf, we have Alpha=1-exp(-b*tf+a). Solving this for a,

a = ln(1-Alpha)+b*tf.

Replacing t with tf and dY/dt with Beta in the equation for dY/dt above and solving for b, the following result is obtained:

$$b = Beta/(1-Alpha).$$

The significant features of the smoldering phase are illustrated by figure 6.4.2.1.

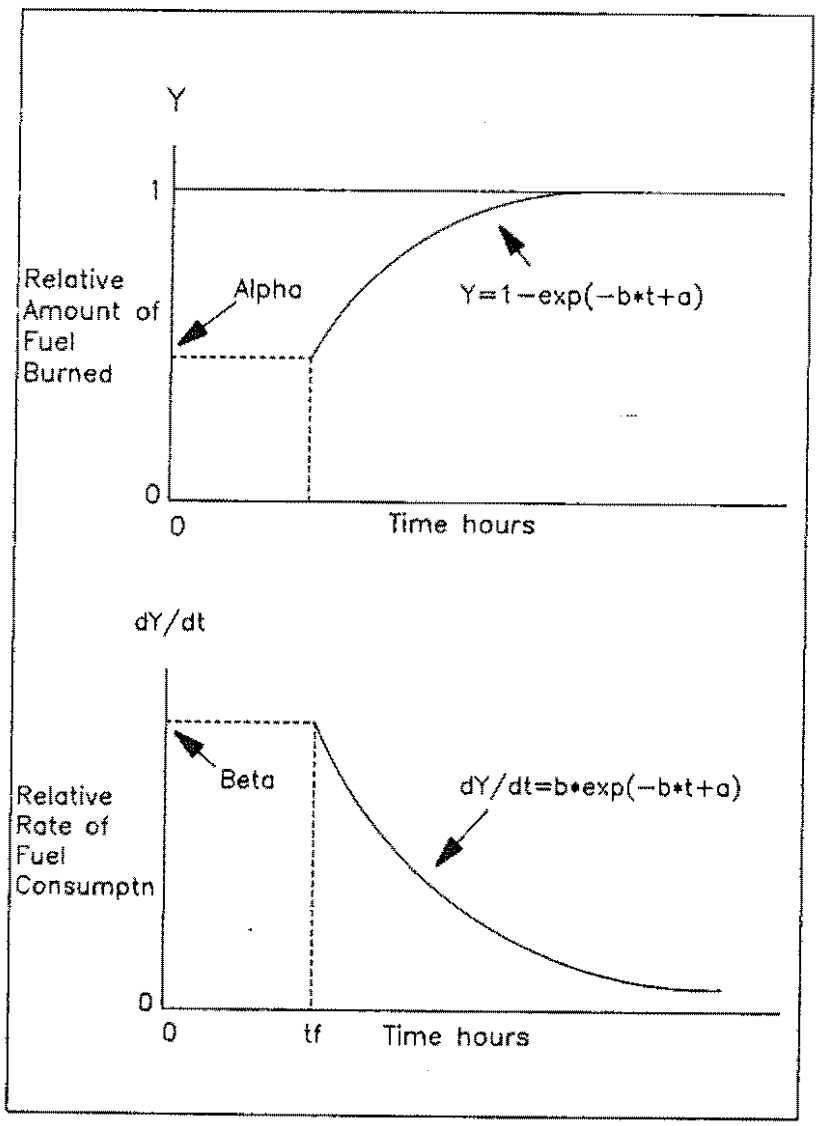


Figure 6.4.2.1. The significant features of the smoldering phase model.

6.4.2.2 Flaming phase, first model.-- The rate of consumption during the flaming phase is reflected by the size, abundance, and moisture content of the available fine fuels. In a fuel bed that consists of a high proportion of fine fuels, it is expected that the fire intensity will grow rapidly to a maximum and have a short residence time in comparison to the duration of the smoldering phase of combustion. The fine fuels would burn out coincident with the time of maximum fire intensity (designated by tf). The rapid rate of fuel consumption would occur largely because of the large ratio of surface area to volume of the fine fuels. Thus, boundary conditions expected are Y(0)=0 and Y'(0)=0. Again, we designate Y(tf)=Alpha, Y'(tf)=Beta. The fire intensity (rate of energy release) is expected to increase linearly and can be expressed by dY/dt=m*t+n. The integrated form of the linear equation is then derived:

$$Y=0.5*m*t^2+n*t+t+constant$$

Since the curve is to go through the origin, the integration constant is 0. Let t=tf, Y(tf)=Alpha=0.5*tf*Beta. We are led to two equations:

$$0.5*tf*Beta=0.5m*tf^2+n*ttf, \quad \text{and}$$
$$Beta=m*tf+n.$$

Solving these for m and n, we get m=Beta/tf and m=0. So the formulas for the flaming phase are:

$$Y = 0.5*(Beta/tf)*t^2, \quad \text{and}$$
$$Y' = Beta/tf)*t.$$

The next step involves equating these formulas at the point of intersection with the formulas Y=1-exp(-b*t+a) and Y=b*exp(-b*t+a) for the smoldering phase.

First, connecting the formulas for Y, we obtain:

$$1-\exp(-b*tf+a)=0.5*(Beta/tf)tf^2$$

Connecting up the derivative formulas, we obtain:

$$\exp(-b*tf+a)=Beta/b$$

Solving these equations simultaneously for a and b, we obtain:

$$b=Beta/(1-0.5*Beta*tf), \quad \text{and}$$
$$a=b*tf+\ln(Beta/b).$$

These values can then be used in the formulas for the smoldering phase. The inputs are tf and Beta. Figure 6.4.2.2 illustrates the significant features of this model. If we assume: (1) the fire has multiple ignition points in the fuel bed, and (2) that the front of the fire spreads at a constant rate from the points of ignition, and (3) that due to the rapid rate of ignition, the fuel is being consumed on this flame front, m, then this model seems to correspond somewhat to physical reality. The intensity is proportional to time as would be expected since the burning takes place only on the circumferences of circles, and these circumferences are proportional to the radii which are in turn proportional to the time. The total amount of fuel consumed is proportional to the square of time, and this makes sense since the fuel will be consumed along the boundaries of circles ever increasing in size which will all come together at the time tf. The areas increase proportional to the time.

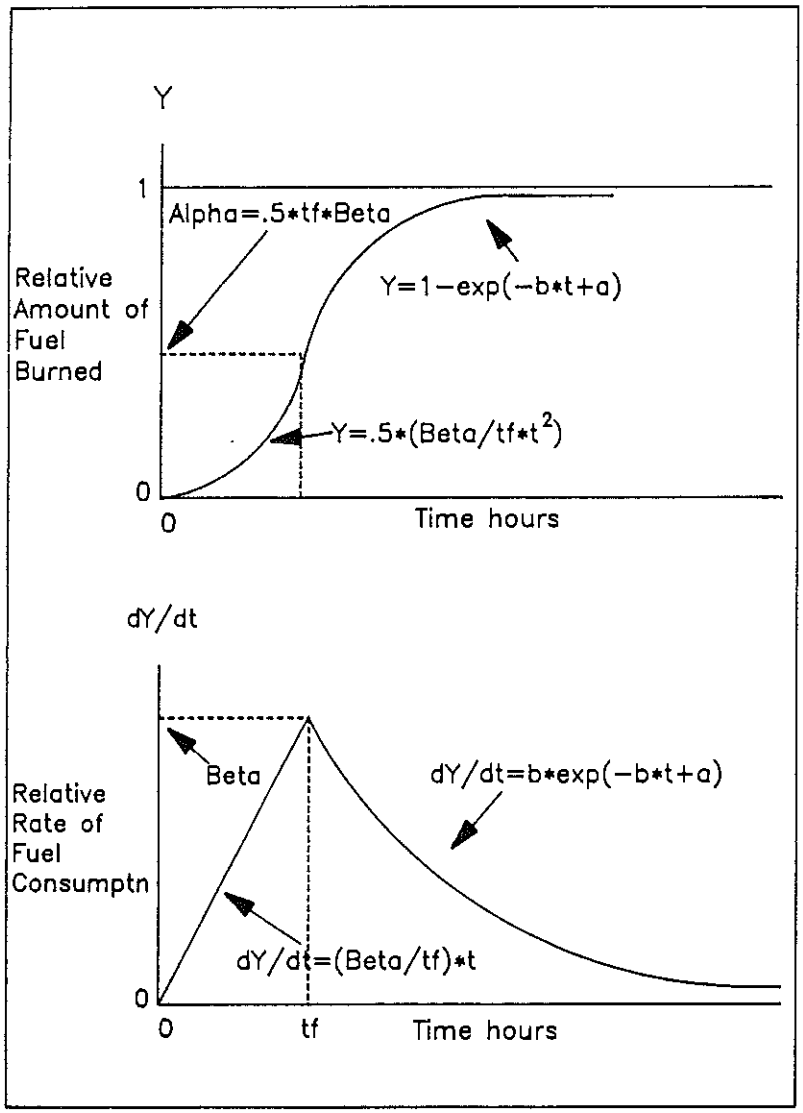


Figure 6.4.2.2. The significant features of the flaming phase--first model.

6.4.2.3 Flaming phase, second model.-- Usually, one can expect that the fine fuels will be exhausted over a period of time. The smallest burn out first and the largest lasting somewhat longer. This would make tf the time for the end of the flaming phase to be later than the time for the maximum rate of intensity of the burn. (Here, tf the

time for the end of flaming phase is the time when all the fine fuels regardless of size are consumed.) Several models for this kind of flaming phase have been constructed; the most satisfactory of which is demonstrated below. We have not been able, up until now, to relate this to any physical situation, and it should be looked upon as having usefulness only because it seems to fit observed data quite nicely. We have good reason to expect Y(0)=0, Y'(0)=0, and Y''(0)=0 from graphs of empirical data. Y(ft)=Alpha, Y'(tf)=Beta, and Y''(tf)=Gamma where Alpha and Beta are as before and Gamma=-b*exp(-b*tf+a), the value of Y"(tf). We have six conditions which are enough to solve for the six coefficients of the fifth degree polynomial:

$$Y=A*t^5+B*t^4+C*t^3+D*t^2+E*t+F$$

The first three conditions force D=E=F. Using the last three boundary conditions, we are led to the following system of equations:

$$A*tf^5+B*tf^4+C*tf^3=Alpha$$
$$5*A*tf^4+4*B*tf^3+3*C*tf^2=Beta, \text{ and}$$
$$20*A\&tf^3+12*B*tf^2+6*C*tf=Gamma.$$

When we solve these simultaneously, we obtain the following formulas:

$$A=(Gamma*tftf^2-6*Beta*tf+12*Alpha)/(2*tf^5)$$
$$B=(-15*Alpha+7*Beta*tf-Gamma*tf^2)/(tf^4)$$
$$C=(Alpha-A*tf^5-B*tf\text{^}4)/(tf^3).$$

With A, B, and C as given above, Our model is now:

$$Y=A*t^5+B*t^4+C*t^3, \quad \text{and} \quad Y'=5*A*t^4+4*B\&t^3+ 3*C*t^2$$

Figure 6.4.2.3 illustrates the features of this model.

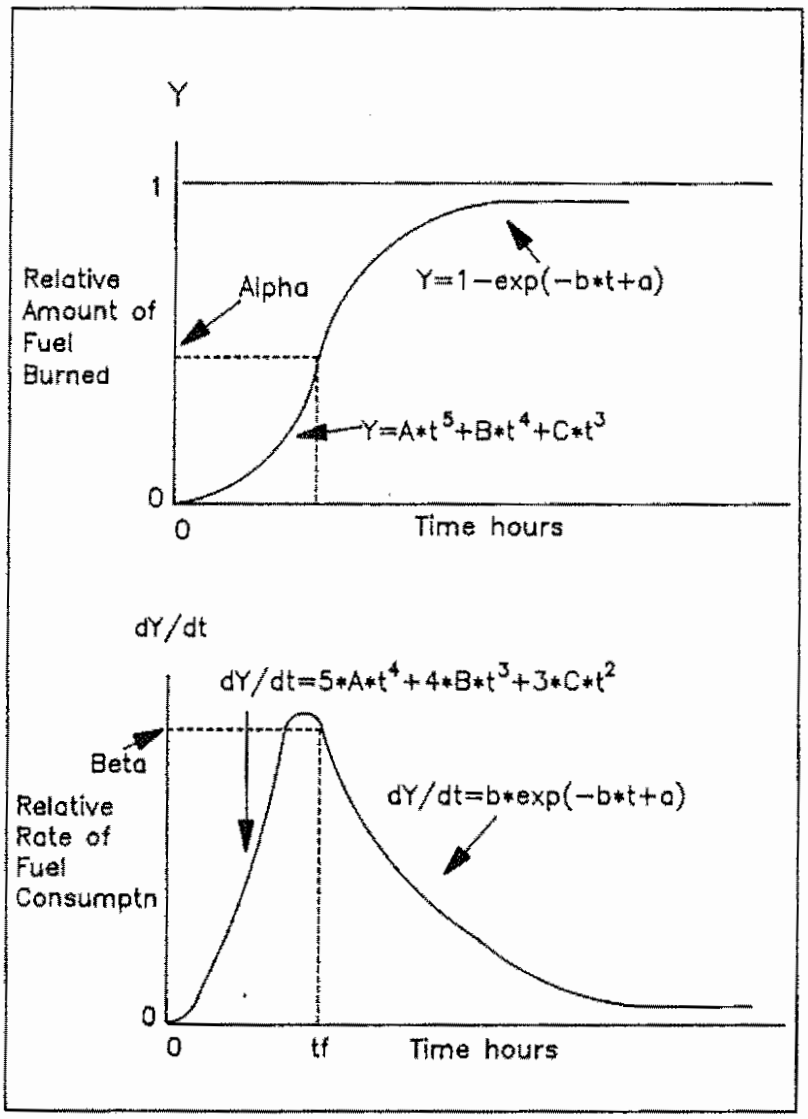


Figure 6.4.2.3. The significant features of the flaming phase--second model.

6.4.3 Summary of Models

The success of our model depends on being able to supply reasonable values for Alpha, Beta, and tf. Alpha should depend mostly on the amount of fine fuels that are expected to burn. Beta should depend on the amount of large fuels that are expected to burn. The situation with tf is more difficult. The flaming burnout time is a function of:

1. Proportion of fine fuels.
2. Size distribution of fine fuels.
3. Moisture content conditions of the fuels.
4. Weather conditions.

The model has been tested against the real time fuel consumption curves for twelve of the tests. Two plots for each of the twelve tests are provided in Appendix G. One plot is of the relative rate of fuel consumption, and the other is of cumulative fuel consumption. The data in table 6.4.2 were used to drive the model for each respective test.

Table 6.4.2. Values for tf, Alpha, Beta, and maximum relative rate of fuel consumption for the models plotted in Appendix G.

Unit Name	tf	Alpha	Beta	Max. Rate consumption (relative)
LB1	.142	.197	1.59	2.1
GHA	.400	.624	2.00	2.5
WHH	.303	.596	1.70	3.0
RSP	.258	.524	2.50	3.1
VIC	.233	.541	2.00	3.6
LL2	.200	.617	2.40	4.8
LB4	.198	.203	2.92	3.0
CC2	.230	.443	1.60	3.0
LB3	.146	.431	2.85	4.3
LB2	.167	.647	4.00	5.9
CPC	.250	.470	2.20	2.8
CC1	.124	.519	3.20	8.5

7.0 APPLICATION OF RESULTS

No other emissions characterization research has resulted in a body of information more extensive or reliable than that contained in this report. The information herein forms the basic data set from which a diversity of continuing research and reporting will be performed.

The results presented in this report are utilized by a diversity of client groups: land management agencies; air resource managers; air quality regulators; and air quality- and atmospheric sciences-related research groups.

The compilation of air pollutant emission factors published by the U.S. Environmental Protection Agency is regularly updated with results from this research (EPA 1980). The document, called AP-42, is the national standard reference for such information.

Recently, the USDA Forest Service released an extensive environmental impact statement relating to the long-term, cumulative effects of vegetation management programs in the Pacific Northwest Region (region six). All sections of that document related to air quality concerns used information that was derived directly from the research reported here (USDA Forest Service 1988). Further, the emissions data from this research has been (and continues to be) utilized by the USDA Forest Service in the preparation of the Forest Plans for every national forest in Region Six.

Fuels management personnel in the states of Oregon and Washington use this information daily in the preparation of environmental assessments and fire prescriptions for prescribed burning projects. Every individual prescribed burning operation in the state of Oregon must be preceded by the submittal of a smoke management report. These reports

include estimates of emissions utilizing data from this research.

An emissions inventory system in both Oregon and Washington includes numerous estimates of daily and annual emissions based on emission factors presented in this report.

State agencies using results directly from this research include Oregon Department of Environmental Quality; Washington Department of Natural Resources; Washington Department of Ecology; California Air Resources Board; California Dept. Forestry and Fire Protection (including Los Angeles County Fire Department).

These data are regularly utilized by numerous federal agencies, including: U.S. Environmental Protection Agency; U.S. Dept. of Interior, Bureau of Land Management; Defense Nuclear Agency; U.S. Dept. of Interior, National Park Service. In addition, USDA Forest Service personnel throughout the United States regularly consult this research work unit for information now reported in this document.

Estimates of the effects of biomass utilization practices on air pollution from prescribed burning have depended on these data for emissions estimates.

Numerous smoke dispersion modeling efforts utilize emission factors and source strength calculations presented in this report. It is expected that any future development work in plume rise modeling and dispersion modeling will depend on this research for emissions production information.

8.0 REFERENCES

Bollen, W.B. 1974. Soil microbes. In: Gen. Tech. Rep. PNW-24. Environmental effects of forest residues management in the Pacific Northwest, a state-of-knowledge compendium. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. B-1/b-41.

Brown, J.K. 1972. Field test of a rate-of-spread model in slash fuels. Res. Pap. INT-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station.

Byram, G.M. 1959. Combustion of forest fuels. In: Davis, K.P., ed. Forest fire: control and use. New York: McGraw Hill: 61-89.

Comery, J.A 1981 Elemental carbon deposition and flux from prescribed burning on a longleaf pine site in Florida. Seattle, WA: University of Washington. (Master of Science Thesis).

Core, J.E. 1981. Receptor model technical series Volume II. Chemical mass balance. EPA 450/4-81-0166. Research Triangle Park, NC:Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency. June.

Culver, C.J.; Pickford, S.G. 1980. Atmospheric losses of nutrients from burning forest litter. Cooperative Agreement No. 132. Final Report. Seattle, WA: University of Washington College of Forest Resources.

Edmonds, R.L.; Driver, C.H.; Vogt, D.J. 1980. Decomposition of logging residues: Final report to U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Forest Residues Research. Seattle, WA: University of Washington.

EKONO Inc. (Unknown) Wood fired boiler systems for space heating. Volume I: Design and evaluation. Final Report, U.S. Department of Agriculture, Forest Service Contract No. 53-91S8-6495. p. 235.

Grier, C. 1975. Wildfire effects on nutrient distribution and leaching in a coniferous ecosystem. Can. Jour. Soil Sci. 5:599-607.

Hardy, C.C. 1986. Fuel quantification for emissions research. Study Plan PNW-86-11-(2) on file at the Forest Science Laboratory, Seattle, WA. January.

Jenkins, P.G. 1983. Aerosol characterization and source determination in the Mt. Rainier area. In: Proceedings, Pacific Northwest International Section of the Air Pollution Control Association; Seattle, WA: November 1983. [Place of publication unknown]. [Publisher unknown].

Nelson, Jr., R.M. 1982. An evaluation of the carbon balance technique for estimating emission factors and fuel consumption in forest fuels. Res. Pap. SE-231. Asheville, NC: U.S. Department of Agriculture, Forest Service, S;outheastern Forest Experiment Station. 9 p.

Norusis, M.J.; SPSS Inc. 1988. SPSS/PC+ Version 2.0 base manual for the IBM PC/XT/AT and PS/2; SPSS Inc. Chicago, Illinois.

Ottmar, R.D. 1983. Predicting fuel consumption by fire stages to reduce smoke from slash fires. In: Proceedings, annual meeting of the Northwest Fire Council; 1983 November 21-22; Olympia, WA. Portland, OR: Northwest Fire Council: 87-106.

Ottmar, R.D.; Little, S.N.; Ohmann, J.L. 1985 Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. In: Proceedings, 8th conference on fire and forest meteorology. Bethesda, MD. April 1985.

Pickford, S.G.; Ward, D.E.; Lundeen, J. 1976. Emissions from burning forest floor fuelbeds: instrumentation, initial results, and analytical procedures. Cooperative Agreement No. 116. Final Report. Seattle, WA: University of Washington, College of Forest Resources.

Radke, L. K.; Lyons, J. H.; Hegg, D. A.; and others. 1986. Airborne monitoring and smoke characterization of prescribed fires on forest lands in western Washington and Oregon. [In Press?] Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Sandberg, D.V. 1980. Duff reduction by prescribed underburning in Douglas-fir. Res. Pap. PNW-272. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station.

Sandberg, D.V.; Ottmar, R.D. 1983. Slash burning and fuel consumption in the Douglas-fir subregion. In: Proceedings of the 7th conference on fire and forest meteorology. Ft. Collins, CO. April 1983.

USDA Forest Service. 1988. Managing competing and unwanted vegetation, final environmental impact statement. USDA Forest Service, Pacific Northwest Region, Portland, Oregon.

U.S. Environmental Protection Agency. 1980. Compilation of air pollutant emission factors--AP-42. U.S. Environmental Protection Agency, Research Triangle Park, N.C.

Ward, D.E. 1981. Emissions from the combustion of residual fuels. Study Plan PNW-81-1-(B-1). On file at the Forest Science Laboratory, Seattle, WA. May.

Ward, D.E.; Hardy, C.C. 1986. Advances in the characterization and control of emissions from prescribed broadcast fires of coniferous species logging slash on clearcut units. Final report, Project EPA DW12390110-01-3/DOE DE-A179-83BP12869, on file at Forest Science Laboratory, Seattle, WA. January.

Ward, D.E.; Hardy, C.C. 1984. Advances in the characterization and control of emissions from prescribed fires. In: Proceedings, annual meeting of the Pacific Northwest Internation Section of the Air Pollution Control Association, San Francisco, CA. Feb. 1984.

-- APPENDIX A --

Concentrations By Fuel Type

APPENDIX A.1--Douglas-fir/hemlock Fuel Type

Fire	Phase	Concentrations					
		PM	PM2.5	CO	CO2	CH4	NMHC
		-(Mg/m3)-				(PPM)	
CAT	Flame	23.0	19.4	146.2	1350.0	4.1	0.9
HEBO	Flame	32.0	21.7	112.4	1241.3	8.8	2.7
MAR1	Flame	35.5	18.4	133.4	1374.7	5.1	1.9
MAR2	Flame						
DL1	Flame	28.3		199.3	2566.2		
DL2	Flame	45.0	21.3	189.9	3712.2	11.3	4.1
BE1	Flame	3.9	2.4	21.2	346.1	1.7	0.6
BE2	Flame	16.6	8.4	88.1	1959.6	5.7	1.3
BE3	Flame	12.4	3.4	72.3	2898.8	3.1	1.9
WCB1	Flame	28.1	20.7	256.2	4467.0	14.7	4.4
WCB2	Flame	32.8	13.2	179.4	3094.4	13.6	4.7
WCB3	Flame						
CAT	Smolder	5.7	7.1	71.8	339.1	4.3	0.7
HEBO	Smolder	1.8	2.0	29.1	113.3	1.7	0.2
MAR1	Smolder	22.4	15.0	202.7	879.1	12.1	2.3
MAR2	Smolder	1.7		17.9	37.5	0.2	0.1
DL1	Smolder	3.3		29.2	198.0		
DL2	Smolder	7.2	5.9	89.2	419.2	3.6	1.3
BE1	Smolder	8.0	6.0	75.7	318.6	6.5	1.7
BE2	Smolder	10.1	7.4	110.3	475.7	7.0	0.7
BE3	Smolder	31.4	23.0	317.8	1295.1	20.1	4.5
WCB1	Smolder	3.7	2.4	69.5	204.6	2.8	0.4
WCB2	Smolder	10.4	5.9	126.4	397.4	7.4	2.5
WCB3	Smolder						
CAT	Fire	11.2	12.3	115.5	663.5	6.1	1.1
HEBO	Fire	9.5	8.6	93.0	486.3	5.8	1.0
MAR1	Fire	26.0	16.1	190.5	1016.0	10.7	2.3
MAR2	Fire						
DL1	Fire						
DL2	Fire	24.0	16.7	227.8	1593.8	9.9	3.6
BE1	Fire	7.2	5.2	64.3	324.9	5.5	1.5
BE2	Fire	15.1	10.4	148.3	913.1	9.4	1.1
BE3	Fire	30.4	21.3	298.7	1632.1	18.7	4.3
WCB1	Fire	28.1	20.7	256.2	4467.0	14.7	4.4
WCB2	Fire	29.5	14.8	277.4	1810.7	17.4	5.9
WCB3	Fire						

APPENDIX A.2--Hardwood Fuel Type

Fire Phase	Concentrations					
	PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)		(PPM)			
GHA Flame	11.7	6.2	41.2	1559.8	2.9	1.1
EAA Flame	9.7	4.3	20.3	447.8	1.5	1.0
VIC Flame	7.6	5.5	36.0	1343.6	2.4	1.0
CPC Flame	16.6	2.8	77.8	2560.0	5.1	2.0
LB1 Flame	14.2	10.2	86.2	1574.3	7.7	3.4
LB2 Flame	13.2	7.9	37.7	551.8	3.1	1.1
LB3 Flame			212.7	3946.6	20.9	8.1
LB4 Flame			40.3	1115.0	3.8	2.1
GHA Smolder	13.8	9.0	129.5	711.5	11.4	2.7
EAA Smolder	11.3	5.6	70.2	438.4	5.0	1.8
VIC Smolder	5.1	3.8	38.1	222.5	4.2	1.1
CPC Smolder	9.3	6.6	80.1	452.3	7.4	2.2
LB1 Smolder	22.8	13.5	111.1	713.3	10.5	3.1
LB2 Smolder	1.9	1.1	9.1	19.5	0.9	0.1
LB3 Smolder	5.8	3.6	60.1	336.0	5.9	1.6
LB4 Smolder	6.6	3.6	51.5	272.6	4.7	1.7
GHA Fire	18.4	11.9	166.6	1038.5	14.7	3.5
EAA Fire	10.8	5.3	64.5	421.8	4.6	1.7
VIC Fire	10.8	8.0	74.6	734.0	7.7	2.1
CPC Fire	22.2	14.2	179.2	1382.1	16.3	4.8
LB1 Fire	27.3	16.5	136.9	1093.2	12.8	4.0
LB2 Fire	10.1	5.9	38.9	265.2	3.6	0.8
LB3 Fire	32.5	20.3	186.8	2076.2	18.3	5.8
LB4 Fire	14.8	8.1	93.6	638.0	8.6	3.1

APPENDIX A.3--Long-needled Pine Fuel Type

Fire Phase	Concentrations					
	PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)				(PPM)	
LL1 Flame						
LL2 Flame	18.6	13.6	96.5	1783.4	5.2	2.5
CC1 Flame	28.2	16.6	101.2	2477.7	6.2	2.5
CC2 Flame	13.6	2.9	49.8	1726.5	3.0	1.3
LL1 Smolder						
LL2 Smolder	9.5	6.5	52.3	232.4	3.7	1.2
CC1 Smolder	4.3	2.4	26.7	214.8	2.7	0.5
CC2 Smolder	14.1	6.8	30.9	281.7	3.4	0.7
LL1 Fire						
LL2 Fire	21.6	15.0	117.6	951.1	7.9	2.9
CC1 Fire	18.9	10.8	92.3	1310.7	7.8	1.8
CC2 Fire	28.4	12.7	67.5	957.9	6.8	1.6

APPENDIX A.4--Mixed Conifer Fuel Type

Fire Phase	Concentrations					
	PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)				(PPM)	
HESS Flame	19.9	7.2	46.4	1244.7	4.9	2.0
RSP Flame	7.4	3.8	19.1	1060.2	1.7	0.6
WHH Flame		7.7	23.9	1397.9	2.1	0.8
HESS Smolder	8.2	5.5	47.6	275.0	4.4	1.3
RSP Smolder	8.1	5.0	54.4	499.2	6.7	1.9
WHH Smolder	7.8	6.9	80.6	552.3	10.1	2.4
HESS Fire	17.4	10.4	86.6	708.9	8.2	2.6
RSP Fire	8.8	5.2	48.4	764.8	5.7	1.7
WHH Fire	12.5	9.9	106.4	909.4	13.2	3.2

APPENDIX A.5--Tractor-piled Fuel Type

Fire Phase	Concentrations					
	PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)				(PPM)	
PIL1 Flame	4.3	2.6	23.2	570.0	2.5	0.9
PIL2 Flame	0.6	0.4	0.7	133.1	0.1	0.0
PIL3 Flame	3.5	1.8	18.7	842.5	1.7	0.6
PIL4 Flame	13.9	7.7	22.9	1942.4	1.5	0.5
PIL1 Smold	2.4	1.7	22.1	200.8	3.1	0.8
PIL2 Smolder	1.5	0.9	9.4	91.0	1.2	0.4
PIL3 Smolder	7.4	0.0	50.5	368.5	6.9	1.6
PIL4 Smolder	3.4	2.4	44.9	382.3	6.1	1.4
PIL1 Fire	3.6	2.3	27.2	379.3	3.5	1.0
PIL2 Fire	1.6	0.6	4.9	112.2	0.6	0.2
PIL3 Fire	7.2		47.4	585.4	6.2	1.5
PIL4 Fire	9.3	6.4	107.4	1074.2	14.4	3.3

APPENDIX A.6--Crane-piled Fuel Type

Fire Phase	Concentrations					
	PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)				(PPM)	
SKY1 Flame	2.7	1.5	7.2	406.5	1.9	0.7
SKY2 Flame	6.3	3.0	24.2	377.7	3.8	1.2
SKY3 Flame	4.8	2.7	22.0	405.9	3.3	0.9
SKY4 Flame	4.9	2.5	19.6	358.8	3.2	1.0
SKY1 Smold						
SKY2 Smolder	5.8	4.4	27.2	262.3	6.3	1.7
SKY3 Smolder	8.8	5.7	39.6	285.6	8.8	2.0
SKY4 Smolder						
SKY1 Fire						
SKY2 Fire	6.2	4.1	27.2	317.3	5.6	1.6
SKY3 Fire	7.5	4.7	34.0	340.7	6.9	1.6
SKY4 Fire						

-- APPENDIX B --

Content of PM2.5

APPENDIX B.1--Douglas-fir/hemlock Fuel Type

Fire	Phase	Na	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Br	Ag	Cd	Sn	Pb
		Percent of PM2.5																				
CAT	Flame		0.102	0.094		0.204	0.568	0.589	0.201				0.018	0.032								
HEBO	Flame		0.101	0.109		0.403	1.054	1.960	0.030				0.008	0.018								
MAR1	Flame		0.164	0.189		0.375	1.048	1.323	0.099				0.006	0.039								
MAR2	Flame																					
DL1	Flame		0.057	0.047		0.280	0.313	1.002	0.078				0.007	0.003								
DL2	Flame		0.305	0.200		0.576	0.707	2.433	0.809				0.078	0.035								
BB1	Flame	9.200	0.070	0.040		0.150	0.150	0.200	0.080	0.130	0.010	0.020	0.060	0.020	0.010	0.010	0.060	0.030				0.110
BB2	Flame	0.902	0.084	0.050		0.254	0.391	1.435	0.102	0.160	0.018	0.042	0.075	0.044	0.007	0.007	0.091	0.046				0.127
BB3	Flame	2.149	0.205	0.125		0.495	0.476	2.606	0.250	0.608	0.286	0.459	0.090	0.346	0.020	0.020	0.284	0.074				0.320
WCB1	Flame	0.920	0.044	0.026		0.483	0.637	1.936	0.050	0.080	0.015	0.018	0.017	0.016	0.005	0.005	0.094	0.065				0.066
WCB2	Flame	0.500	0.065	0.034		0.191	0.215	0.706	0.116	0.110	0.015	0.025	0.022	0.017	0.005	0.005	0.061	0.025				0.146
WCB3	Flame																					
CAT	Smolder		0.371	0.677		0.227	0.204	0.219	0.399				0.050	0.273								
HEBO	Smolder		0.139	0.231		0.174	0.154	0.164	0.015				0.002	0.024								
MAR1	Smolder		0.036	0.037		0.084	0.199	0.171	0.049				0.002	0.014								
MAR2	Smolder		0.076	0.248		0.025	0.185	0.064	0.133				0.015	0.097								
DL1	Smolder		0.103	0.311		0.109	0.039	0.123	0.118				0.013	0.066								
DL2	Smolder		0.086	0.105		0.037	0.037	0.216	0.066				0.002	0.030								
BB1	Smolder	0.601	0.039	0.061		0.091	0.053	0.058	0.056	0.085	0.013	0.015	0.020	0.076	0.003	0.003	0.003	0.038				0.040
BB2	Smolder	0.855	0.063	0.047		0.168	0.116	0.060	0.183	0.144	0.013	0.026	0.032	0.026	0.010	0.010	0.016	0.014				0.107
BB3	Smolder	0.128	0.014	0.010		0.038	0.081	0.158	0.102	0.016		0.010	0.014	0.010								0.010
WCB1	Smolder	1.463	0.124	0.084		0.142	0.144	0.097	0.151	0.260	0.031	0.051	0.051	0.039	0.016	0.016	0.026	0.033				0.150
WCB2	Smolder	0.613	0.060	0.030		0.153	0.085	0.057	0.121	0.116	0.064	0.020	0.022	0.020	0.010	0.010	0.018	0.014				0.083
WCB3	Smolder																					
CAT	Fire		0.295	0.512		0.220	0.307	0.323	0.343				0.041	0.205								
HEBO	Fire		0.124	0.183		0.264	0.506	0.866	0.021				0.004	0.022								
MAR1	Fire		0.071	0.078		0.163	0.430	0.485	0.063				0.003	0.021								
MAR2	Fire																					
DL1	Fire																					
DL2	Fire		0.138	0.127		0.164	0.195	0.740	0.242				0.020	0.031								
BB1	Fire	1.436	0.042	0.059		0.097	0.062	0.072	0.058	0.090	0.013	0.015	0.023	0.071	0.004	0.004	0.009	0.037				0.047
BB2	Fire	0.862	0.066	0.047		0.180	0.155	0.254	0.171	0.146	0.014	0.028	0.038	0.028	0.010	0.010	0.027	0.019				0.109
BB3	Fire	0.179	0.019	0.013		0.050	0.091	0.220	0.106	0.031	0.007	0.021	0.016	0.018	0.001	0.001	0.007	0.002				0.018
WCB1	Fire																					
WCB2	Fire	0.576	0.062	0.031		0.166	0.128	0.273	0.119	0.114	0.048	0.021	0.022	0.019	0.008	0.008	0.032	0.018				0.104

APPENDIX B.2--Hardwood Fuel Type

Fire	Phase	Na	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Br	Ag	Cd	Sn	Pb
		Percent of PM2.5																				
GHA	Flame		0.216	0.297	0.205	0.954	2.770	5.353	0.023	0.011	0.005	0.005	0.041	0.033	0.002	0.009	0.208	0.168	0.042	0.002	0.022	0.090
BAA	Flame		1.253	1.459	0.614	0.791	0.924	2.987	0.012	0.081	0.024	0.116	0.079	0.617	0.144	0.102	0.130	0.324	0.430	1.067	0.464	0.999
VIC	Flame		0.159	0.777	0.584				1.083	0.024	0.000	0.006	0.025	0.073	0.010	0.016	0.550	0.143	0.000	0.000	0.066	0.356
CPC	Flame																					
LB1	Flame		0.109	0.214	0.093	0.937	2.961	3.734	0.020	0.000	0.000	0.000	0.003	0.006	0.006	0.019	0.100	0.119	0.038	0.038	0.033	0.022
LB2	Flame		0.077	0.029	0.053	0.371	0.831	1.783	0.034	0.008	0.013	0.000	0.001	0.000	0.000	0.000	0.027	0.026	0.026	0.056	0.000	0.000
LB3	Flame		0.044	0.087	0.052	0.403	0.979	1.307	0.055	0.001	0.000	0.000	0.006	0.003	0.000	0.000	0.031	0.043	0.003	0.001	0.006	0.006
LB4	Flame		0.100	0.124	0.060	0.550	0.885	1.245	0.042	0.006	0.000	0.000	0.002	0.016	0.003	0.000	0.034	0.041	0.002	0.019	0.010	0.002
GHA	Smolder		0.187	0.203	0.121	0.313	0.578	0.885	0.132	0.011	0.003	0.006	0.033	0.044	0.002	0.002	0.018	0.031	0.037	0.058	0.006	0.043
BAA	Smolder		0.239	0.492	0.139	0.461	0.860	0.889	0.146	0.015	0.001	0.005	0.023	0.115	0.002	0.002	0.014	0.033	0.004	0.000	0.015	0.032
VIC	Smolder		0.538	1.295	0.261	0.294	0.409	1.729		0.029	0.009	0.010	0.004	0.256	0.012	0.003	0.057	0.004	0.033	0.344	0.196	0.026
CPC	Smolder		0.196	0.206	0.050	0.039	0.156	0.119	0.063	0.037	0.016	0.001	0.025	0.014	0.003	0.000	0.009	0.026	0.108	0.074	0.073	0.124
LB1	Smolder		0.042	0.074	0.035	0.276	0.564	0.407	0.032	0.002	0.000	0.001	0.003	0.014	0.001	0.000	0.007	0.015	0.006	0.000	0.002	0.001
LB2	Smolder		0.031	0.152	0.031	0.120	0.196	0.314	0.045	0.002	0.003	0.000	0.001	0.010	0.000	0.000	0.006	0.010	0.005	0.031	0.000	0.000
LB3	Smolder		0.113	0.165	0.055	1.249	0.431	0.198	0.013	0.007	0.000	0.000	0.000	0.039	0.001	0.000	0.000	0.018	0.041	0.023	0.036	0.015
LB4	Smolder		0.101	0.101	0.053	1.269	0.550	0.077	0.009	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.002	0.016	0.010	0.001	0.018	0.004
GHA	Fire		0.189	0.207	0.125	0.344	0.683	1.099	0.127	0.011	0.003	0.006	0.033	0.043	0.002	0.002	0.027	0.037	0.037	0.056	0.007	0.046
BAA	Fire		0.286	0.537	0.162	0.476	0.863	0.987	0.139	0.018	0.003	0.010	0.026	0.139	0.009	0.007	0.019	0.047	0.024	0.050	0.036	0.077
VIC	Fire		0.469	1.201	0.320	0.932	2.069	4.800	1.034	0.028	0.007	0.009	0.008	0.223	0.012	0.005	0.146	0.029	0.027	0.282	0.172	0.086
CPC	Fire																					
LB1	Fire		0.051	0.092	0.043	0.362	0.875	0.839	0.030	0.002	0.000	0.001	0.003	0.013	0.002	0.002	0.019	0.028	0.010	0.005	0.006	0.004
LB2	Fire		0.055	0.089	0.042	0.249	0.523	1.069	0.039	0.005	0.008	0.000	0.001	0.005	0.000	0.000	0.017	0.018	0.016	0.044	0.000	0.000
LB3	Fire		0.113	0.165	0.055	1.249	0.431	0.198	0.013	0.007	0.000	0.000	0.000	0.039	0.001	0.000	0.000	0.018	0.041	0.023	0.036	0.015
LB4	Fire		0.101	0.101	0.053	1.269	0.550	0.077	0.009	0.000	0.000	0.000	0.000	0.003	0.000	0.000	0.002	0.016	0.010	0.001	0.018	0.004

APPENDIX B.3--Long-needled Pine

Fire	Phase	Na	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Br	Ag	Cd	Sn	Pb
		Percent of PM2.5																				
LL1	Flame		0.066	0.093	0.053	0.201	0.202	0.626	0.084	0.003	0.001	0.000	0.014	0.010	0.000	0.000	0.031	0.008	0.007	0.011	0.007	0.019
LL2	Flame		0.039	0.072	0.067	0.481	0.347	1.960	0.055	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.090	0.016	0.026	0.038	0.000	0.006
CC1	Flame		0.090	0.204	0.129	0.901	0.913	3.428	0.146	0.018	0.007	0.001	0.025	0.018	0.010	0.000	0.187	0.062	0.030	0.114	0.011	0.150
CC2	Flame		0.129	0.240	0.102	0.640	0.754	2.396	0.163	0.017	0.005	0.010	0.018	0.010	0.007	0.000	0.151	0.046	0.049	0.016	0.036	0.097
LL1	Smolder																					
LL2	Smolder		0.075	0.033	0.024	0.066	0.058	0.107	0.020	0.000	0.000	0.000	0.002	0.001	0.000	0.000	0.007	0.003	0.009	0.003	0.001	0.004
CC1	Smolder		0.184	0.343	0.070	0.136	0.226	0.497	0.183	0.014	0.003	0.001	0.017	0.166	0.002	0.000	0.023	0.009	0.032	0.019	0.028	0.026
CC2	Smolder		0.056	0.066	0.050	0.283	0.392	0.899	0.018	0.001	0.001	0.000	0.004	0.004	0.002	0.000	0.044	0.012	0.013	0.022	0.023	0.026
LL1	Fire																					
LL2	Fire		0.065	0.044	0.036	0.185	0.140	0.635	0.029	0.000	0.000	0.000	0.004	0.001	0.000	0.000	0.030	0.007	0.013	0.013	0.001	0.005
CC1	Fire		0.135	0.270	0.101	0.538	0.587	2.037	0.163	0.016	0.005	0.001	0.021	0.088	0.006	0.000	0.109	0.037	0.031	0.069	0.019	0.091
CC2	Fire		0.061	0.077	0.053	0.305	0.414	0.991	0.027	0.002	0.001	0.001	0.005	0.004	0.002	0.000	0.051	0.014	0.015	0.022	0.024	0.030

APPENDIX B.4--Mixed Conifer Fuel Type

Fire	Phase	Na	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Br	Ag	Cd	Sn	Pb
		Percent of PM2.5																				
HESS	Flame		0.116	0.109	0.110	0.492	0.367	1.868	0.077	0.004	0.007	0.007	0.014	0.023	0.001	0.002	0.128	0.023	0.076	0.104	0.111	0.012
RSP	Flame		0.142	0.104	0.174	0.724	1.159	4.150	0.193	0.010	0.001	0.004	0.036	0.011	0.000	0.002	0.237	0.041	0.053	0.123	0.000	0.049
WHH	Flame		0.100	0.109	0.160	0.496	0.691	2.416	0.183	0.009	0.006	0.002	0.035	0.016	0.002	0.002	0.257	0.034	0.021	0.055	0.023	0.037
HESS	Smolder		0.021	0.026	0.030	0.047	0.055	0.084	0.026	0.001	0.000	0.001	0.003	0.003	0.000	0.001	0.002	0.000	0.006	0.007	0.001	0.003
RSP	Smolder		0.040	0.059	0.058	0.153	0.183	0.562	0.082	0.003	0.002	0.002	0.013	0.011	0.003	0.002	0.024	0.006	0.020	0.021	0.045	0.009
WHH	Smolder		0.027	0.046	0.036	0.044	0.108	0.232	0.054	0.003	0.000	0.000	0.007	0.010	0.001	0.000	0.008	0.003	0.012	0.020	0.000	0.000
HESS	Fire		0.035	0.038	0.042	0.113	0.101	0.349	0.033	0.002	0.001	0.002	0.005	0.006	0.000	0.002	0.021	0.004	0.016	0.021	0.018	0.005
RSP	Fire		0.067	0.071	0.089	0.304	0.442	1.515	0.112	0.005	0.001	0.003	0.019	0.011	0.002	0.002	0.081	0.016	0.029	0.048	0.033	0.020
WHH	Fire		0.036	0.053	0.050	0.095	0.174	0.481	0.069	0.004	0.001	0.000	0.010	0.011	0.001	0.000	0.036	0.007	0.013	0.024	0.003	0.005

APPENDIX B.5--Tractor-Piled Fuel Type

Fire	Phase	Na	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Br	Ag	Cd	Sn	Pb
		Percent of PM2.5																				
PIL1	Flame		0.193	0.297	0.089	0.531	0.550	2.277	0.545	0.011	0.005	0.000	0.017	0.045	0.000	0.000	0.124	0.055	0.028	0.014	0.000	0.053
PIL2	Flame		0.087	0.215	0.100	0.567	0.763	2.306	0.458	0.000	0.000	0.000	0.059	0.000	0.000	0.020	0.298	0.089	0.285	0.000	0.363	0.070
PIL3	Flame		0.156	0.398	0.160	1.600	1.339	7.177	0.714	0.040	0.012	0.000	0.079	0.040	0.023	0.003	0.505	0.293	0.270	0.222	0.084	0.447
PIL4	Flame		0.287	0.480	0.163	1.102	1.033	3.821	0.758	0.021	0.009	0.000	0.024	0.035	0.020	0.003	0.630	0.148	0.103	0.028	0.337	0.367
PIL1	Smolder		0.050	0.055	0.041	0.265	0.230	0.786	0.073	0.000	0.002	0.000	0.002	0.000	0.000	0.000	0.018	0.009	0.000	0.000	0.000	0.014
PIL2	Smolder		0.063	0.026	0.031	0.182	0.243	0.409	0.059	0.003	0.001	0.000	0.007	0.000	0.002	0.000	0.011	0.014	0.020	0.041	0.000	0.010
PIL3	Smolder																					
PIL4	Smolder		0.054	0.075	0.046	0.236	0.209	0.623	0.081	0.001	0.000	0.000	0.006	0.008	0.078	0.000	0.009	0.012	0.005	0.005	0.000	0.006
PIL1	Fire		0.073	0.095	0.049	0.309	0.282	1.030	0.150	0.002	0.002	0.000	0.004	0.007	0.000	0.000	0.035	0.017	0.005	0.002	0.000	0.020
PIL2	Fire		0.071	0.088	0.054	0.308	0.413	1.029	0.189	0.002	0.001	0.000	0.024	0.000	0.001	0.007	0.105	0.039	0.107	0.028	0.119	0.030
PIL3	Fire																					
PIL4	Fire		0.082	0.123	0.060	0.339	0.307	1.003	0.162	0.004	0.002	0.000	0.008	0.011	0.071	0.000	0.082	0.029	0.016	0.007	0.040	0.048

APPENDIX B.6--Crane-Piled Fuel Type

Fire	Phase	Na	Al	Si	P	S	Cl	K	Ca	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Br	Ag	Cd	Sn	Pb
		Percent of PM2.5																				
SKY1	Flame		0.019	0.000	0.015	0.226	0.188	1.459	0.084	0.000	0.000	0.000	0.023	0.003	0.000	0.002	0.037	0.001	0.000	0.000	0.000	0.000
SKY2	Flame		0.019	0.000	0.006	0.208	0.218	0.939	0.065	0.000	0.001	0.000	0.016	0.009	0.000	0.002	0.038	0.003	0.007	0.003	0.018	0.005
SKY3	Flame		0.023	0.000	0.013	0.204	0.215	1.187	0.052	0.001	0.002	0.001	0.014	0.002	0.000	0.001	0.064	0.004	0.003	0.000	0.000	0.004
SKY4	Flame		0.037	0.062	0.012	0.279	0.163	1.196	0.094	0.003	0.000	0.000	0.023	0.012	0.000	0.000	0.078	0.007	0.009	0.000	0.000	0.018
SKY1	Smolder		0.009	0.020	0.004	0.122	0.118	1.064	0.091	0.001	0.001	0.001	0.024	0.009	0.000	0.001	0.012	0.002	0.009	0.004	0.000	0.003
SKY2	Smolder		0.017	0.007	0.008	0.191	0.167	1.125	0.094	0.002	0.000	0.001	0.020	0.007	0.000	0.002	0.013	0.001	0.008	0.009	0.000	0.005
SKY3	Smolder		0.020	0.024	0.012	0.066	0.065	0.428	0.055	0.002	0.000	0.000	0.010	0.004	0.001	0.001	0.006	0.000	0.000	0.004	0.001	0.000
SKY4	Smolder		0.004	0.000	0.005	0.122	0.077	0.657	0.071	0.001	0.000	0.000	0.017	0.009	0.000	0.000	0.016	0.003	0.000	0.000	0.000	0.004
SKY1	Fire																					
SKY2	Fire		0.018	0.005	0.007	0.196	0.181	1.073	0.086	0.002	0.001	0.001	0.019	0.007	0.000	0.002	0.020	0.002	0.008	0.008	0.005	0.005
SKY3	Fire		0.021	0.019	0.013	0.097	0.099	0.597	0.054	0.002	0.000	0.000	0.011	0.004	0.001	0.001	0.019	0.001	0.001	0.003	0.001	0.001
SKY4	Fire																					

APPENDIX B.7--Douglas-fir/hemlock Fuel Type

Fire	Phase	Organic carbon	Graphitic carbon	Total carbon
		- - - Percent of PM2.5 - - -		
CAT	Flame	50.4	5.6	56.0
HEBO	Flame	42.0	8.0	50.0
MAR1	Flame			
MAR2	Flame			
DL1	Flame			
DL2	Flame	42.0	12.0	54.0
BE1	Flame	30.6	20.0	50.6
BE2	Flame	16.8	40.3	57.1
BE3	Flame	24.9	34.1	58.9
WCB1	Flame	41.9	10.6	52.5
WCB2	Flame	42.8	18.4	61.2
WCB3	Flame			
CAT	Smolder	45.6	3.4	49.0
HEBO	Smolder			
MAR1	Smolder	51.0	2.7	53.7
MAR2	Smolder	36.0	2.7	38.7
DL1	Smolder			
DL2	Smolder	45.0	3.2	48.2
BE1	Smolder	55.6	3.2	58.8
BE2	Smolder	55.1	4.9	60.0
BE3	Smolder	62.6	2.5	65.1
WCB1	Smolder	54.7	4.1	58.8
WCB2	Smolder	61.5	3.6	65.1
WCB3	Smolder			
CAT	Fire	47.0	4.0	51.0
HEBO	Fire	16.4	3.1	19.5
MAR1	Fire	37.1	2.0	39.1
MAR2	Fire			
DL1	Fire			
DL2	Fire	44.3	5.3	49.6
BE1	Fire	53.2	4.8	58.0
BE2	Fire	49.7	9.9	59.6
BE3	Fire	61.6	3.3	64.9
WCB1	Fire			
WCB2	Fire	55.3	8.5	63.8
WCB3	Fire			

APPENDIX B.8--Hardwood Fuel Type

Fire	Phase	Organic carbon	Graphitic carbon	Total carbon
		- - - Percent of PM2.5 - - -		
GHA	Flame			
EAA	Flame			
VIC	Flame			
CPC	Flame			
LB1	Flame	59.1	13.8	72.9
LB2	Flame	58.5	5.9	64.4
LB3	Flame	60.8	10.2	71.0
LB4	Flame	62.7	3.2	65.9
GHA	Smolder			
EAA	Smolder			
VIC	Smolder			
CPC	Smolder	65.0	4.2	69.2
LB1	Smolder	61.5	2.1	63.6
LB2	Smolder	62.6	3.4	66.0
LB3	Smolder	58.2	2.1	60.3
LB4	Smolder	61.0	1.9	62.9
GHA	Fire			
EAA	Fire			
VIC	Fire			
CPC	Fire			
LB1	Fire	61.2	3.6	64.8
LB2	Fire	60.5	4.7	65.2
LB3	Fire	58.2	2.1	60.3
LB4	Fire	61.0	1.9	62.9

APPENDIX B.9--Long-needled Pine

Fire	Phase	Organic carbon	Graphitic carbon	Total carbon
		- - - Percent of PM2.5 - - -		
LL1	Flame	57.2	2.9	60.1
LL2	Flame	50.6	15.4	66.0
CC1	Flame	59.2	11.8	71.0
CC2	Flame	53.2	13.5	66.7
LL1	Smolder			
LL2	Smolder	62.2	3.4	65.6
CC1	Smolder	63.2	3.5	66.7
CC2	Smolder	57.6	5.4	63.0
LL1	Fire			
LL2	Fire	58.9	6.8	65.7
CC1	Fire	61.1	7.9	69.0
CC2	Fire	57.3	5.9	63.2

APPENDIX B.10--Mixed Conifer Fuel Type

Fire	Phase	Organic carbon	Graphitic carbon	Total carbon
		- - - Percent of PM2.5 - - -		
HESS	Flame	57.0	21.6	78.5
RSP	Flame	58.9	37.6	96.5
WHH	Flame	57.1	26.2	83.3
HESS	Smolder	72.0	1.9	73.9
RSP	Smolder	64.5	2.7	67.3
WHH	Smolder	62.3	1.2	63.5
HESS	Fire	69.8	4.8	74.6
RSP	Fire	63.0	12.0	75.0
WHH	Fire	61.8	4.0	65.8

APPENDIX B.11--Tractor-Piled Fuel Type

Fire	Phase	Organic carbon	Graphitic carbon	Total carbon
		- - - Percent of PM2.5 - - -		
PIL1	Flame	47.5	10.7	58.2
PIL2	Flame	52.4	2.7	55.1
PIL3	Flame	42.4	9.1	51.5
PIL4	Flame	53.7	10.2	63.9
PIL1	Smolder	51.5	3.9	55.4
PIL2	Smolder	54.6	1.9	56.5
PIL3	Smolder			
PIL4	Smolder			
PIL1	Fire	50.8	5.0	55.9
PIL2	Fire	53.9	2.2	56.0
PIL3	Fire			
PIL4	Fire			

APPENDIX B.12--Crane-Piled Fuel Type

Fire	Phase	Organic carbon	Graphitic carbon	Total carbon
		- - - Percent of PM2.5 - - -		
SKY1	Flame	58.9	2.6	61.5
SKY2	Flame	54.5	1.8	56.3
SKY3	Flame	61.1	2.3	63.4
SKY4	Flame	64.8	2.5	67.3
SKY1	Smolder	61.5	1.5	63.0
SKY2	Smolder	57.3	0.9	58.2
SKY3	Smolder	59.1	0.7	59.8
SKY4	Smolder	63.5	1.2	64.7
SKY1	Fire			
SKY2	Fire	56.5	1.2	57.7
SKY3	Fire	59.5	1.1	60.6
SKY4	Fire			

-- APPENDIX C --

Emission Factors, Total Carbon Concentration Rate of Fuel Consumption, Rate of Heat Release

APPENDIX C.1--Douglas-fir/hemlock Fuel Type

Fire	Phase	Carbon conc.	Combst Effcy.	Fuel cons.	Heat rate	Emission Factors					
						PM	PM2.5	CO	CO2	CH4	NMHC
		(Mg/m3)		(Kg/m2)	(Kw/m2)	- - - - - -		(G/kg)		- - - - -	
CAT	Flame	746	89.0%	2.7	28.9	15.4	13.0	112	1625	1.8	1.1
HEBO	Flame	683	88.0%	1.3	53.3	23.4	15.9	94	1632	4.2	3.6
MAR1	Flame	755	89.0%	8.5	68.0	23.5	12.2	101	1635	2.2	2.3
MAR2	Flame										
DL1	Flame	1389	90.0%		48.6	10.2		82	1659		
DL2	Flame	1938	94.0%	6.2	83.2	11.6	5.5	56	1720	1.9	1.9
BE1	Flame	182	93.0%	0.8	20.2	10.8	6.6	66	1705	3.0	3.2
BE2	Flame	1012	94.9%	2.8	69.3	8.2	4.2	50	1739	1.9	1.1
BE3	Flame	1461	97.2%	4.0	78.9	4.2	1.2	28	1781	0.7	1.2
WCB1	Flame	2337	93.6%			6.0	4.4	63	1716	2.0	1.7
WCB2	Flame	1624	93.3%	6.3	155.8	10.1	4.1	63	1711	2.7	2.6
WCB3	Flame			0.6	15.2						
CAT	Smolder	207	80.0%	5.2	5.0	13.7	17.1	198	1469	6.7	3.2
HEBO	Smolder	72	77.0%	2.3		12.2	14.0	231	1413	7.8	3.0
MAR1	Smolder	548	78.4%	20.3	38.5	20.4	13.7	211	1439	7.2	3.8
MAR2	Smolder	29	64.3%			29.2		358	1180	1.8	1.8
DL1	Smolder	119	81.4%		1.7	13.8		140	1494		
DL2	Smolder	258	79.4%	9.6	10.0	14.0	11.5	197	1456	4.6	4.6
BE1	Smolder	201	77.5%	3.4	6.8	20.0	14.8	215	1423	10.5	7.8
BE2	Smolder	295	78.9%	5.7	9.8	17.2	12.5	214	1448	7.7	2.2
BE3	Smolder	818	77.5%	12.6	22.7	19.2	14.0	222	1422	8.0	4.9
WCB1	Smolder	137	73.0%			13.3	8.9	289	1339	6.6	2.3
WCB2	Smolder	267	72.9%	4.7	9.0	19.5	11.1	271	1338	9.1	8.3
WCB3	Smolder				12.9						
CAT	Fire	391	83.0%	7.9		14	16	169	1522	5	2
HEBO	Fire	293	81.3%	3.6		16	15	182	1492	7	3
MAR1	Fire	609	81.6%	28.8		21	13	179	1497	6	3
MAR2	Fire										
DL1	Fire										
DL2	Fire	918	85.0%	15.8		13	9	142	1560	4	4
BE1	Fire	197	80.5%	4.2		18	13	186	1478	9	7
BE2	Fire	531	84.1%	8.5		14	10	160	1544	6	2
BE3	Fire	972	82.2%	16.5		16	11	176	1508	6	4
WCB1	Fire	2337	93.5%			6	4	63	1716	2	2
WCB2	Fire	1047	84.6%	11.0		14	7	151	1553	5	5
WCB3	Fire										

APPENDIX C.2--Hardwood Fuel Type

Fire Phase	Carbon conc.	Combst Effcy.	Fuel cons.	Heat rate	Emission Factors					
					PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)		(Kg/m2)	(Kw/m2)	- - - - - -		(G/kg)		- - - - -	
GHA Flame	810	94.3%	2.8	42.3	7.2	3.8	29	1730	1.2	1.3
EAA Flame	241	90.9%	0.5	6.7	20.0	8.9	48	1668	2.0	3.6
VIC Flame	695	94.6%	4.3	74.9	5.4	4.0	30	1736	1.1	1.3
CPC Flame	1332	94.0%	3.7	68.5	6.2	1.1	33	1725	1.3	1.3
LB1 Flame	844	91.2%	4.4	76.1	8.4	6.1	58	1674	3.0	3.6
LB2 Flame	305	88.7%	1.2	18.5	21.7	13.0	71	1627	3.3	3.3
LB3 Flame	2101	91.9%	8.7	118.7			58	1687	3.2	3.4
LB4 Flame	585	93.2%	1.6	30.0			39	1710	2.1	3.2
GHA Smolder	436	79.9%	20.5	49.7	15.8	10.3	170	1466	8.6	5.6
EAA Smolder	265	81.1%	8.9	13.2	21.4	10.6	152	1488	6.2	6.1
VIC Smolder	136	80.0%	5.4	11.0	18.9	14.0	160	1468	10.0	7.0
CPC Smolder	277	80.0%	9.1	26.6	16.9	12.0	165	1468	8.8	7.0
LB1 Smolder	430	81.2%	11.4	30.2	26.5	15.6	148	1489	7.9	6.4
LB2 Smolder	16	59.9%	0.4	1.0	58.3	33.7	326	1098	18.5	7.9
LB3 Smolder	206	79.9%	4.1	7.2	14.1	8.8	167	1465	9.3	6.9
LB4 Smolder	168	79.5%	4.9	5.4	19.6	10.8	176	1460	9.2	8.9
GHA Fire	623	81.6%	23.3		14.8	9.5	153	1498	7.7	5.1
EAA Fire	253	81.7%	9.5		21.4	10.5	146	1498	5.9	6.0
VIC Fire	416	86.4%	9.7		13.0	9.6	103	1586	6.1	4.5
CPC Fire	805	84.1%	12.8		13.8	8.8	127	1543	6.6	5.4
LB1 Fire	637	84.0%	15.8		21.5	13.0	123	1541	6.6	5.7
LB2 Fire	160	81.0%	1.6		31.4	18.5	139	1486	7.4	4.5
LB3 Fire	1153	88.1%	12.7		14.1	8.8	93	1617	5.2	4.5
LB4 Fire	377	82.9%	6.4		19.6	10.8	142	1522	7.4	7.5

APPENDIX C.3--Long-needled Pine Fuel Type

Fire Phase	Carbon conc.	Combst Effcy.	Fuel cons.	Heat rate	Emission Factors					
					PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)		(Kg/m2)	(Kw/m2)	- - - - - -		(G/kg)		- - - - -	
LL1 Flame										
LL2 Flame	955	91.4%	3.2	54.7	9.7	7.1	58	1677	1.8	2.3
CC1 Flame	1311	92.5%	9.6	234.3	10.7	6.3	44	1697	1.5	1.7
CC2 Flame	898	94.1%	5.0	89.1	7.6	1.6	32	1727	1.1	1.3
LL1 Smolder										
LL2 Smolder	151	75.6%	2.7	11.0	31.5	21.4	198	1386	8.1	7.5
CC1 Smolder	125	84.1%	5.8	8.6	17.1	9.5	122	1543	6.9	3.3
CC2 Smolder	166	83.2%	6.0	11.6	42.7	20.5	107	1527	6.7	3.7
LL1 Fire										
LL2 Fire	553	84.2%	5.9		19.6	13.6	122	1545	4.6	4.7
CC1 Fire	718	89.3%	15.4		13.1	7.5	73	1640	3.6	2.3
CC2 Fire	532	88.2%	10.9		26.7	11.9	73	1618	4.2	2.6

APPENDIX C.4--Mixed Conifer Fuel Type

Fire Phase	Carbon conc.	Combst Effcy.	Fuel cons.	Heat rate	Emission Factors					
					PM	PM2.5	CO	CO2	CH4	NMHC
	(Mg/m3)		(Kg/m2)	(Kw/m2)	- - - - - -		(G/kg)		- - - - -	
HESS Flame	656	92.8%	2.8	42.9	15.1	5.5	40	1704	2.5	2.7
RSP Flame	546	95.1%	5.7	84.7	6.8	3.5	20	1745	1.0	1.1
WHH Flame	722	94.7%	3.0	59.9		5.4	19	1739	0.9	1.0
HESS Smolder	169	79.6%	5.5	9.0	24.2	16.2	161	1460	8.6	7.2
RSP Smolder	286	85.4%	6.2	29.1	14.1	8.7	109	1566	7.7	5.9
WHH Smolder	329	82.2%	11.9	19.4	11.9	10.5	140	1508	10.0	6.7
HESS Fire	413	84.1%	8.4		21.1	12.6	120	1543	6.5	5.7
RSP Fire	416	90.0%	11.9		10.6	6.2	66	1651	4.5	3.6
WHH Fire	526	84.7%	14.9		11.9	9.5	116	1554	8.2	5.5

APPENDIX C.5--Tractor-piled Fuel Type

Fire	Phase	Carbon conc.	Combst Effcy.	Fuel cons.	Heat rate	Emission Factors PM	PM2.5	CO	CO2	CH4	NMHC
		(Mg/m3)		(Kg/m2)	(Kw/m2)			(G/kg)			
PIL1	Flame	299	93.2%	1.6	30.0	7.1	4.3	44	1709	2.8	2.8
PIL2	Flame	67	96.6%	26.8	202.2	4.7	2.9	6	1773	0.4	0.0
PIL3	Flame	434	95.0%	22.5	182.8	4.1	2.1	25	1744	1.3	1.3
PIL4	Flame	993	95.8%	8.0	100.0	7.0	3.9	13	1757	0.5	0.5
PIL1	Smold	115	85.6%	4.9	5.4	10.3	7.2	110	1571	8.8	6.0
PIL2	Smolder	52	85.8%	19.4	40.0	14.7	8.4	103	1574	7.5	6.2
PIL3	Smolder	218	82.6%	26.7	67.3	17.0		132	1516	10.3	6.5
PIL4	Smolder	216	86.4%	41.3	66.0	7.8	5.6	119	1586	9.2	5.7
PIL1	Fire	207	89.6%	6.4		8.6	5.7	75	1645	5.6	4.3
PIL2	Fire	60	92.1%	46.2		13.3	5.2	47	1690	3.3	2.6
PIL3	Fire	326	87.9%	49.2		11.1		83	1612	6.2	4.1
PIL4	Fire	605	87.0%	49.3		7.7	5.3	101	1596	7.8	4.9

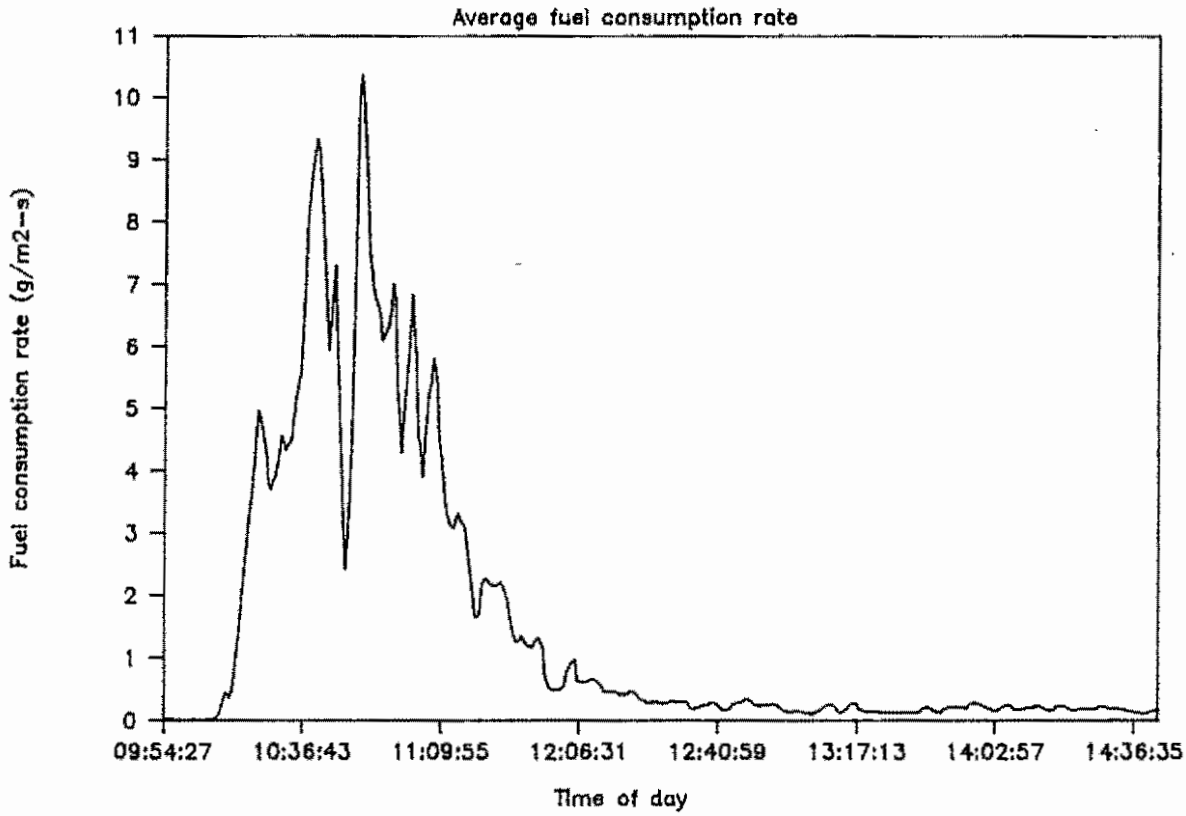
APPENDIX C.6--Crane-piled Fuel Type

Fire	Phase	Carbon conc.	Combst Effcy.	Fuel cons.	Heat rate	Emission Factors PM	PM2.5	CO	CO2	CH4	NMHC
		(Mg/m3)		(Kg/m2)	(Kw/m2)			(G/kg)			
SKY1	Flame	210	94.7%	10.2	26.0	6.5	3.6	19	1738	2.9	3.0
SKY2	Flame	207	89.2%	47.7	189.0	15.1	7.3	67	1637	6.0	5.1
SKY3	Flame	219	90.7%	48.1	286.9	11.0	6.2	58	1665	4.9	3.6
SKY4	Flame	194	90.4%	20.7	73.6	12.5	6.5	58	1659	5.4	4.8
SKY1	Smold	217									
SKY2	Smolder	153	84.0%	61.8	80.9	18.9	14.4	102	1542	13.4	9.8
SKY3	Smolder	173	80.7%	63.2	110.3	25.4	16.5	130	1480	16.6	10.4
SKY4	Smolder	216									
SKY1	Fire	213									
SKY2	Fire	180	86.3%	109.6		17.2	11.3	87	1584	10.2	7.8
SKY3	Fire	196	85.0%	111.3		19.2	12.1	99	1560	11.5	7.5
SKY4	Fire										

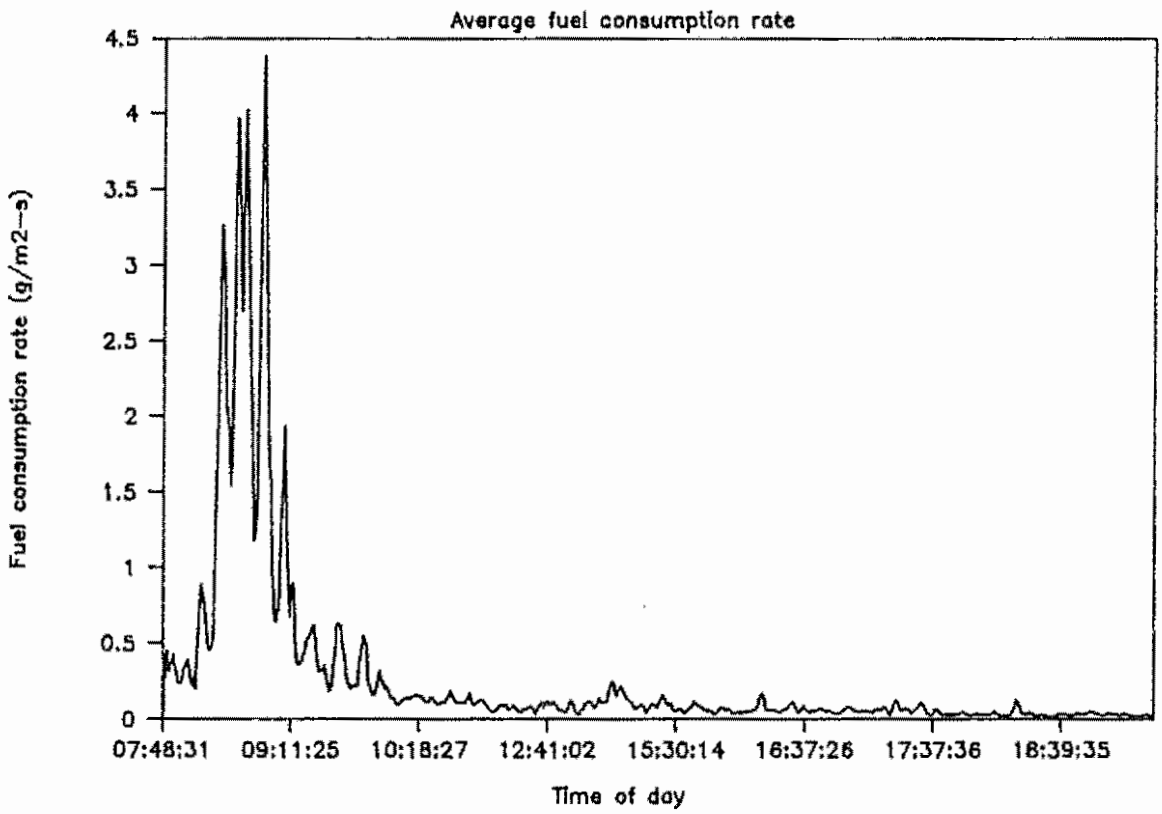
-- APPENDIX D --

Rate of Fuel Consumption Plots
Carbon Flux Technique

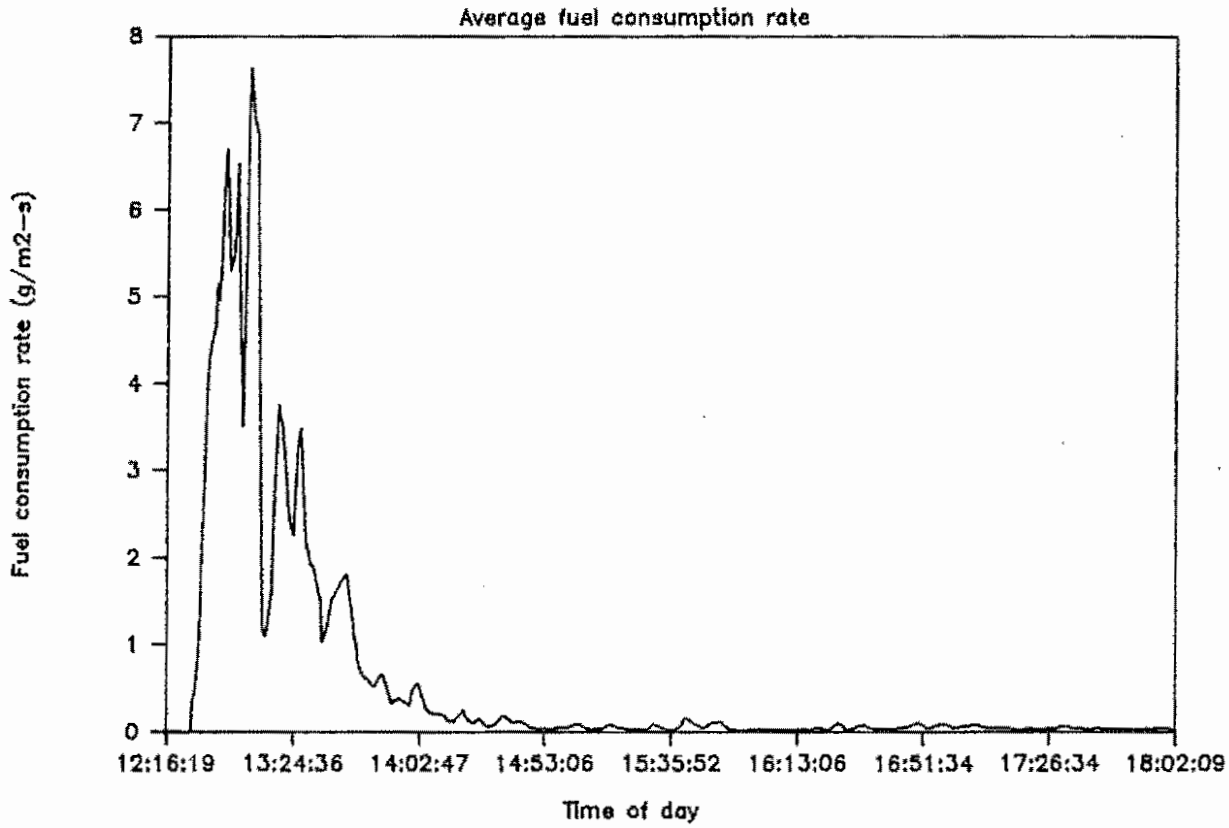
Gauldy Hebo A



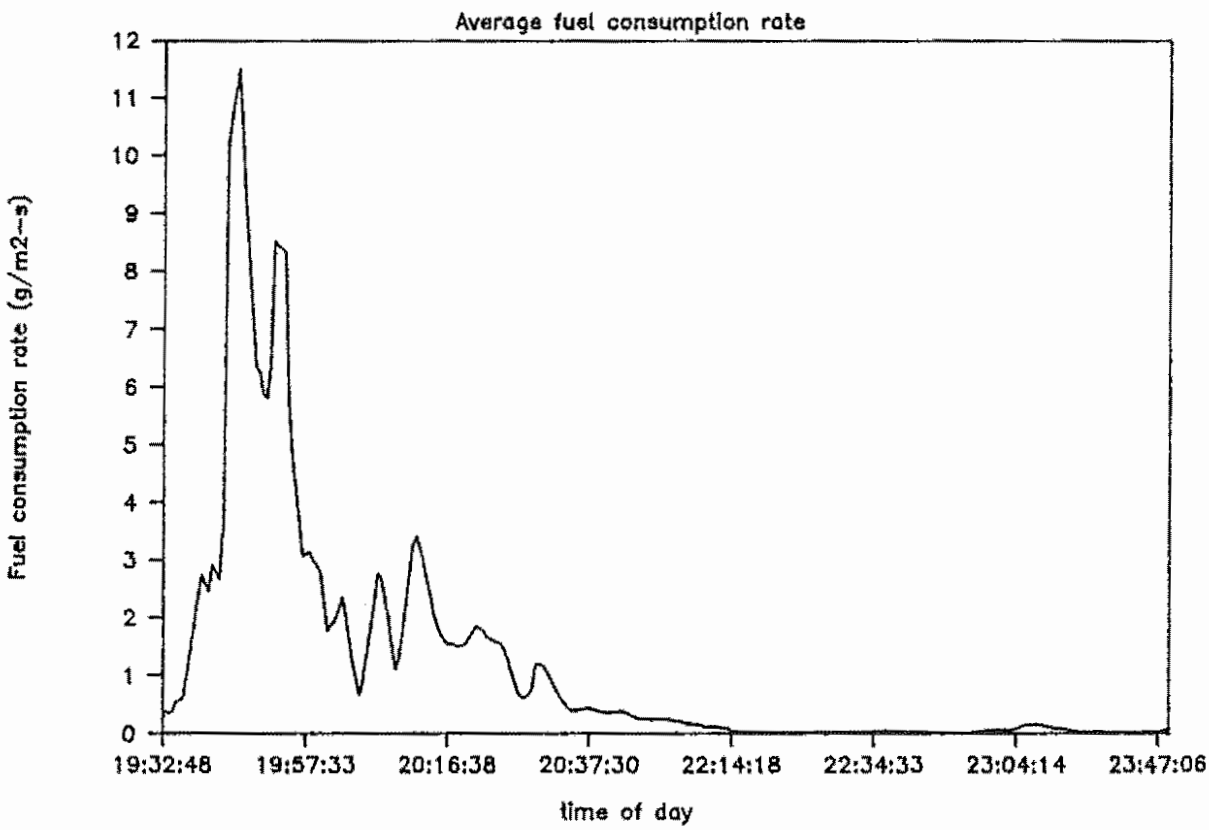
Elder Alder A



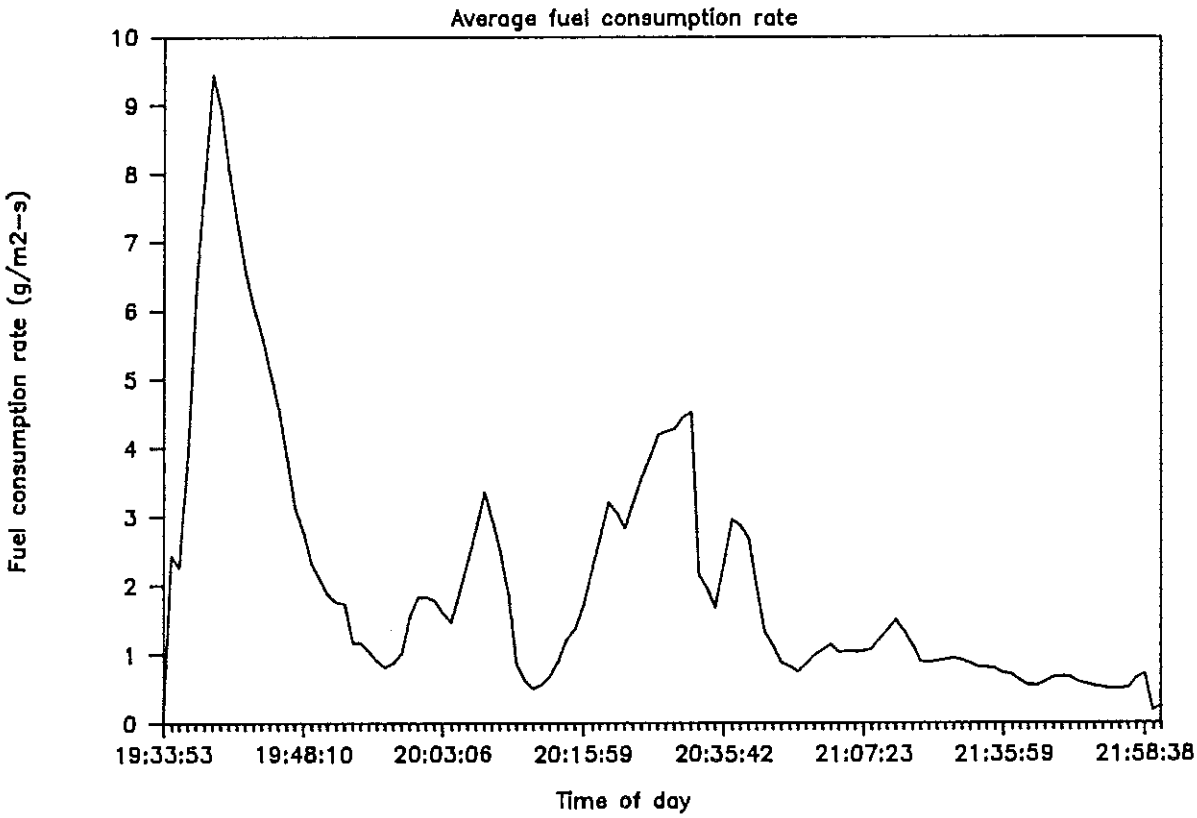
Victoria



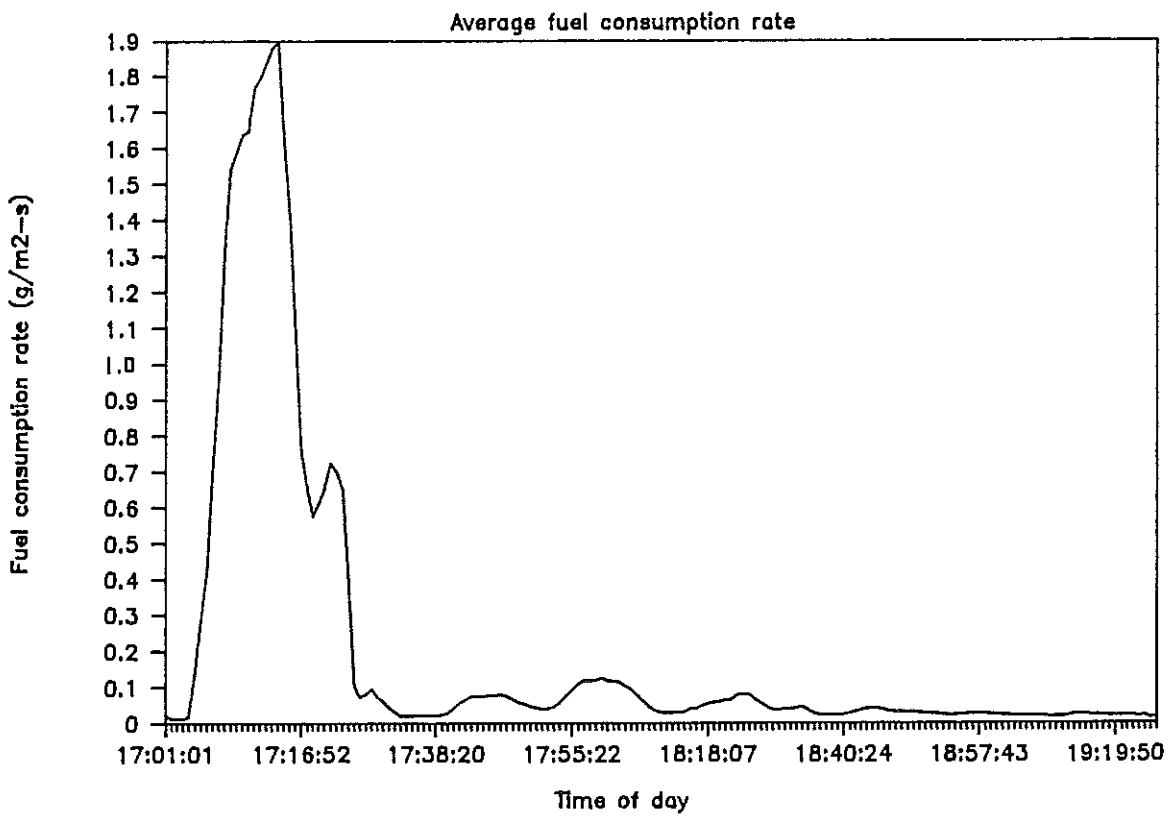
Cedar Pollard



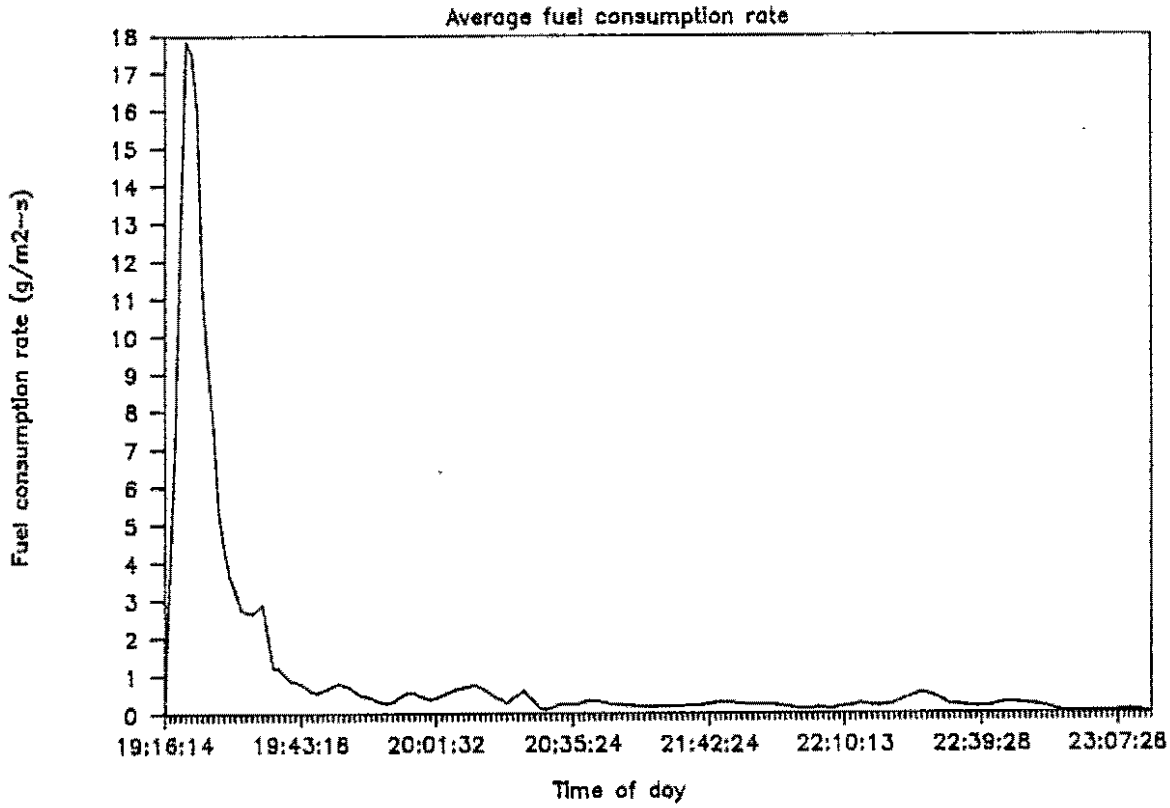
Limestone Boulder 1



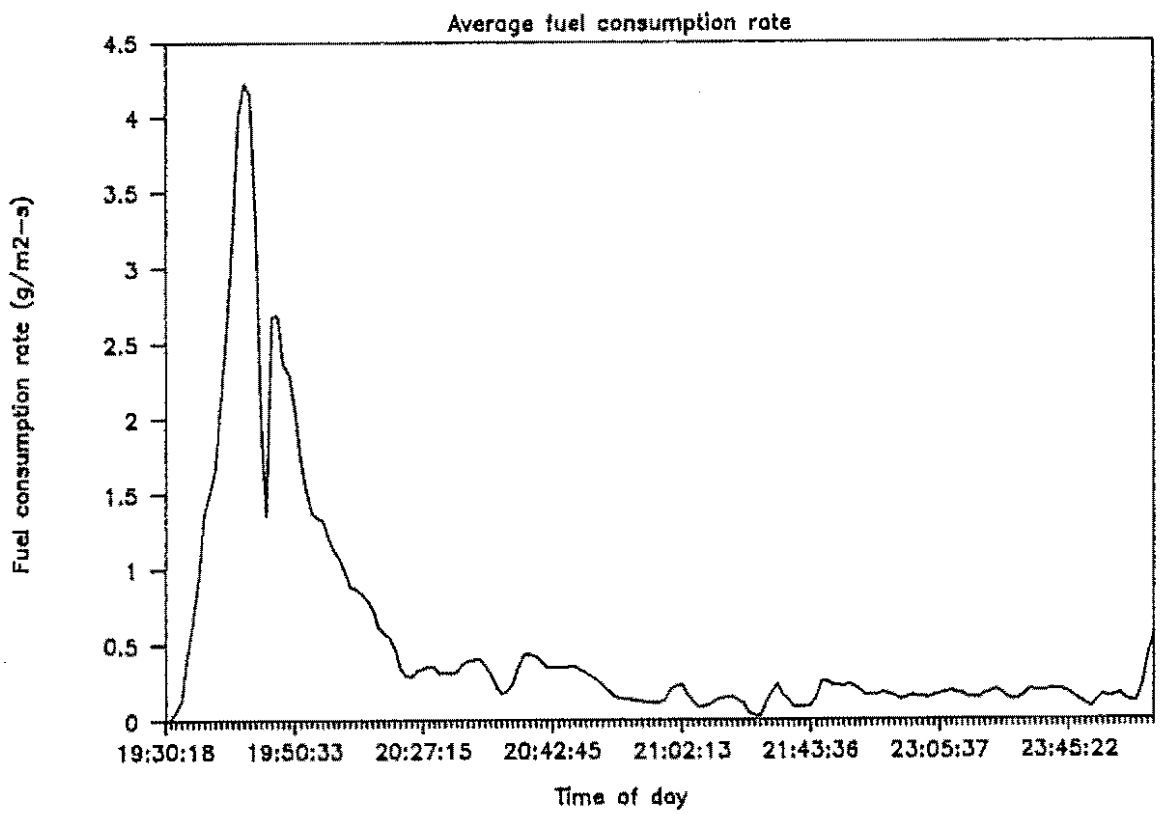
Limestone Boulder 2



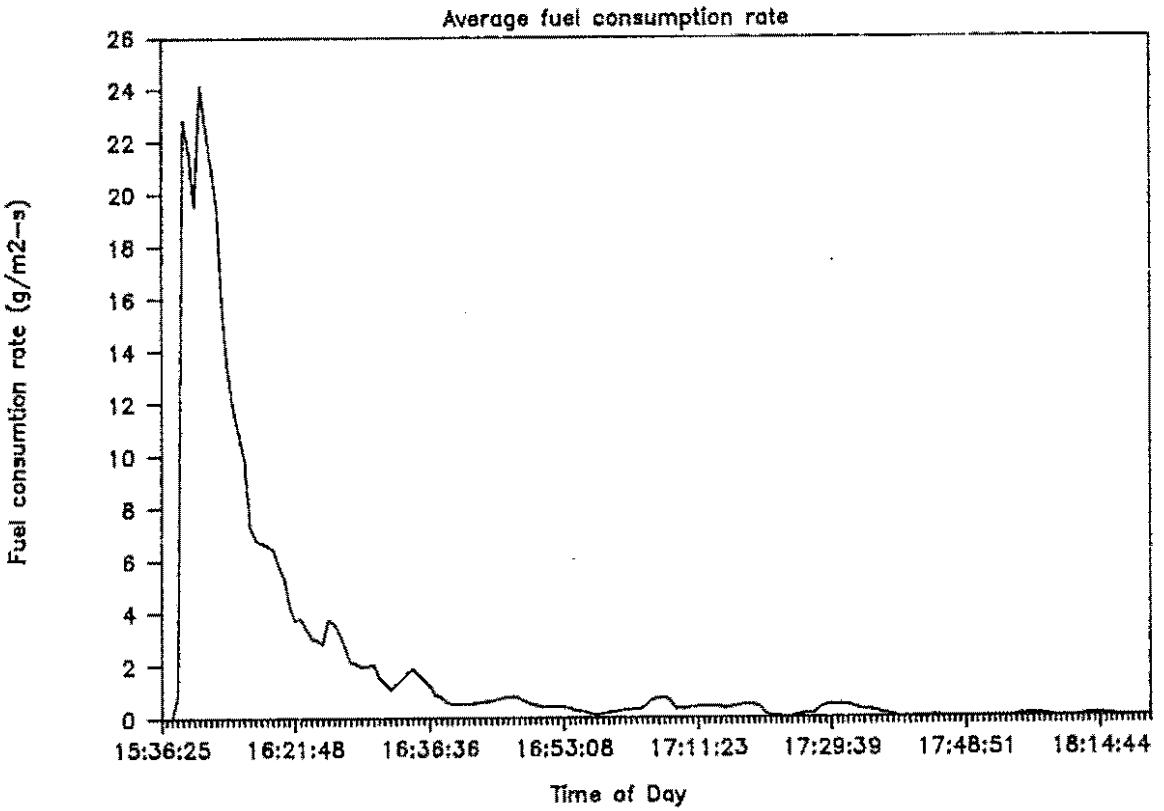
Limestone Boulder 3



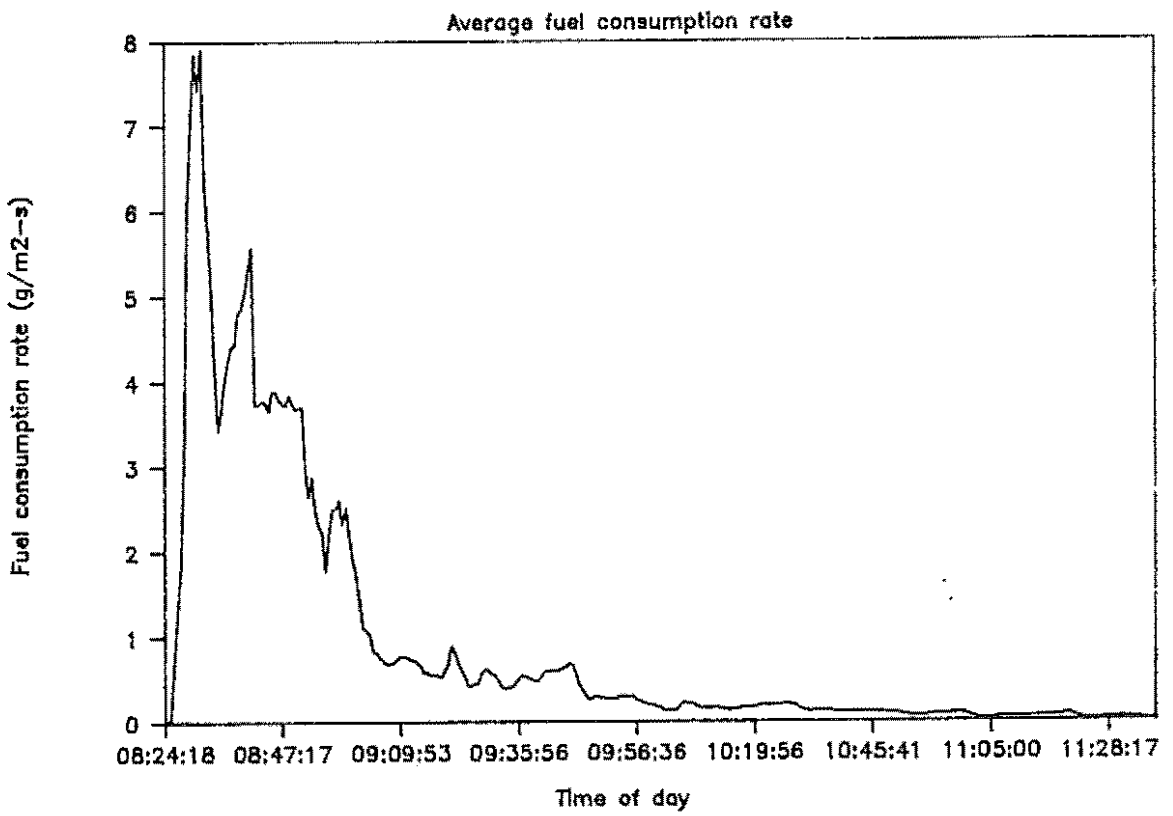
Limestone Boulder 4



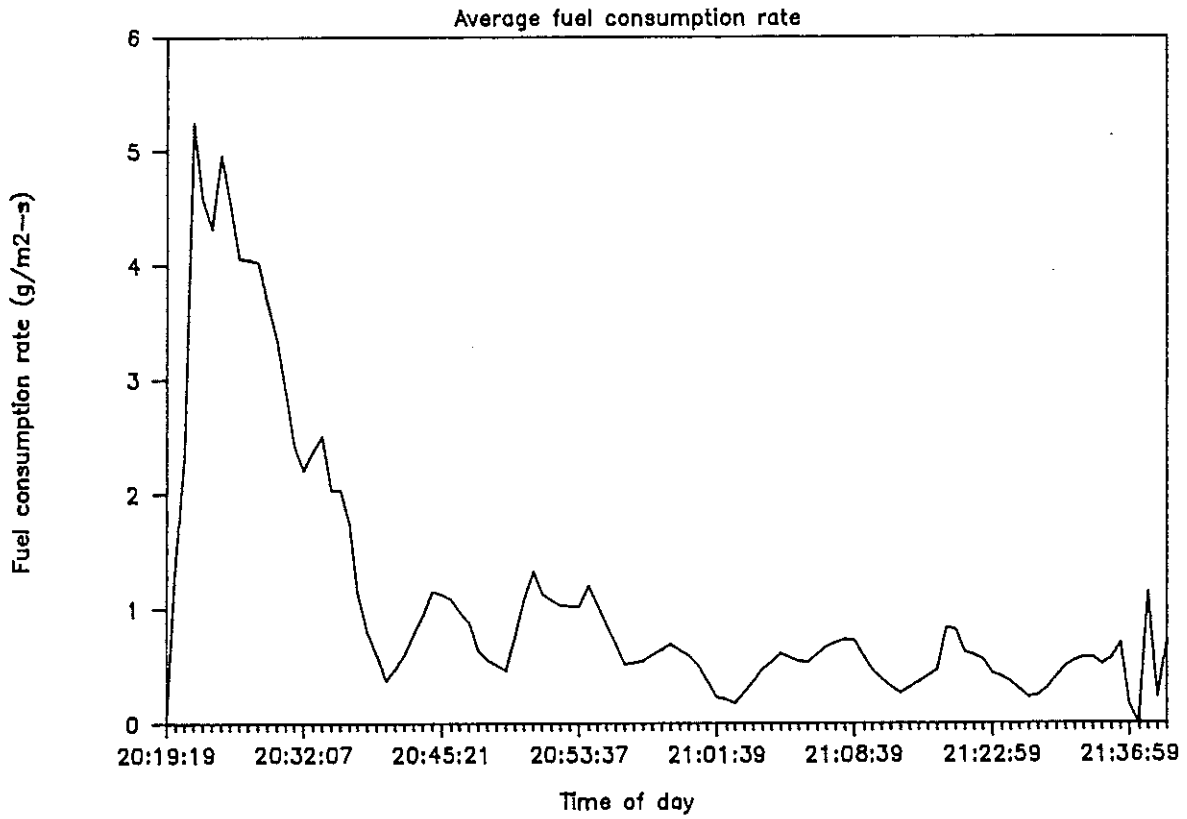
Cole's Corner 1



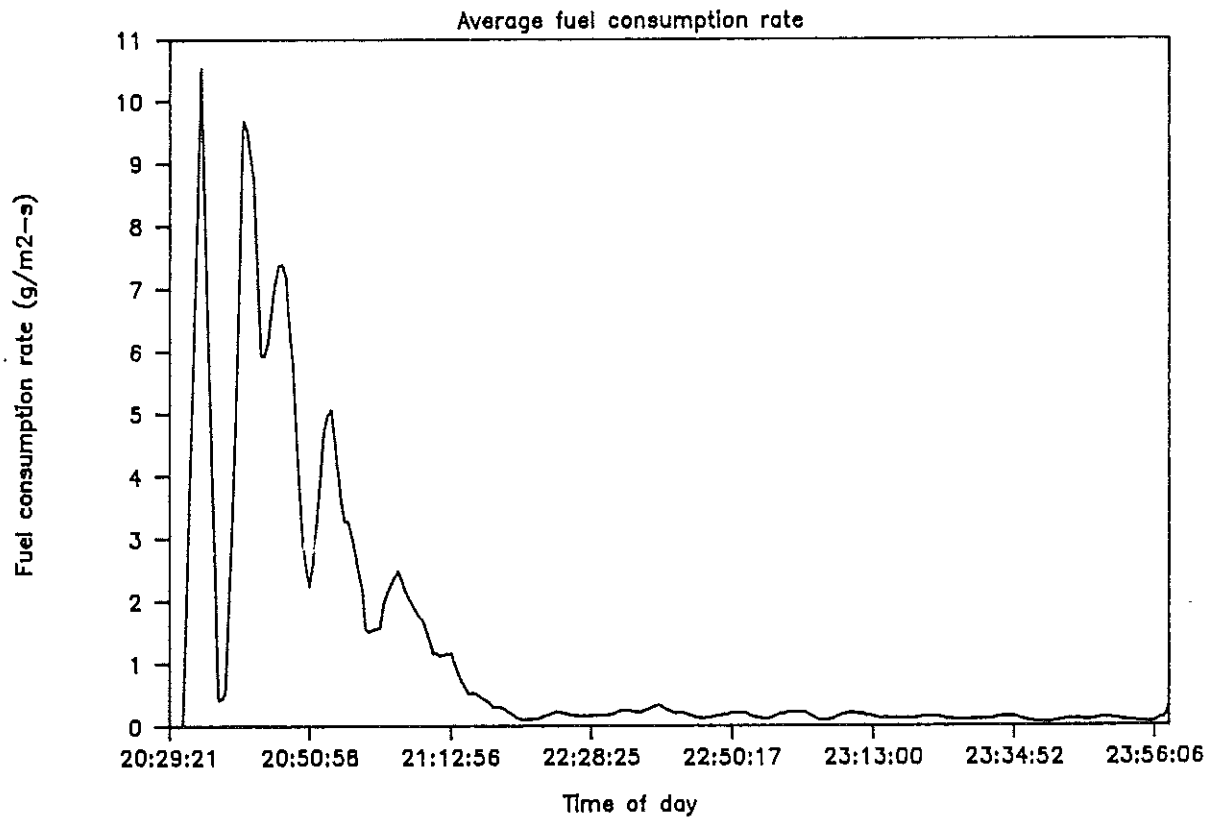
Cole's Corner 2



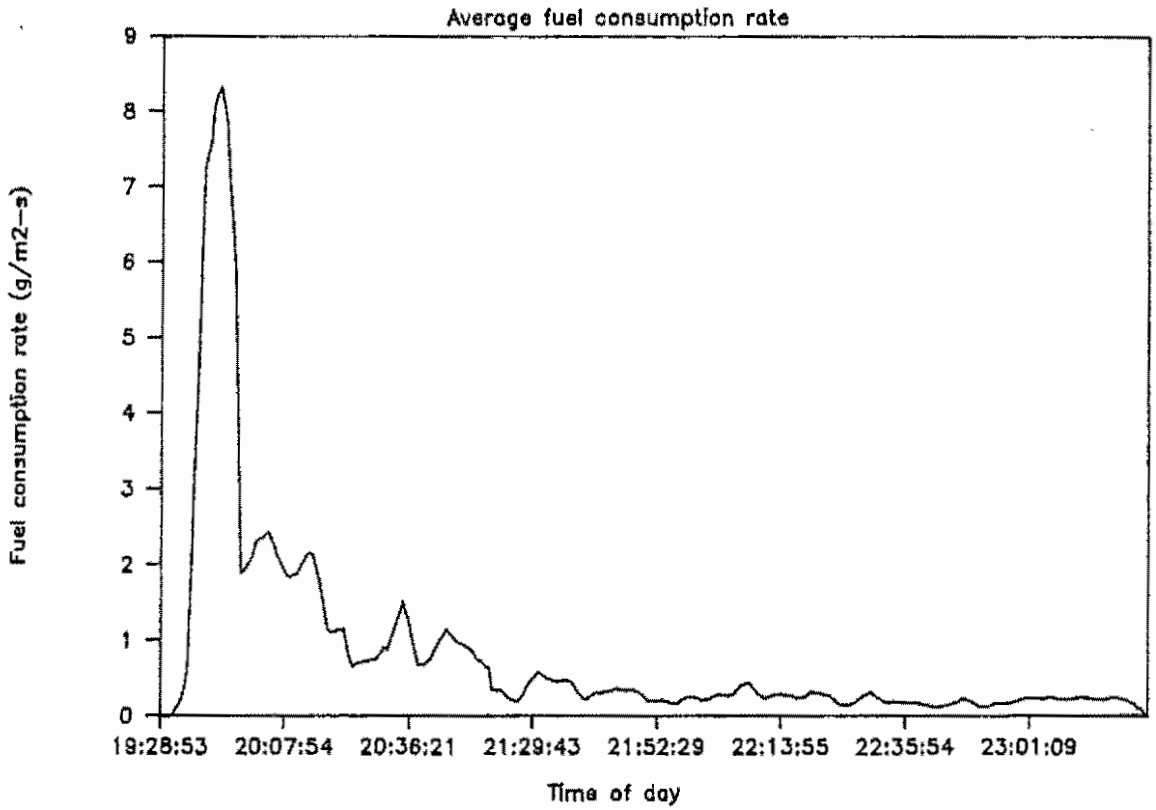
Lolo 2



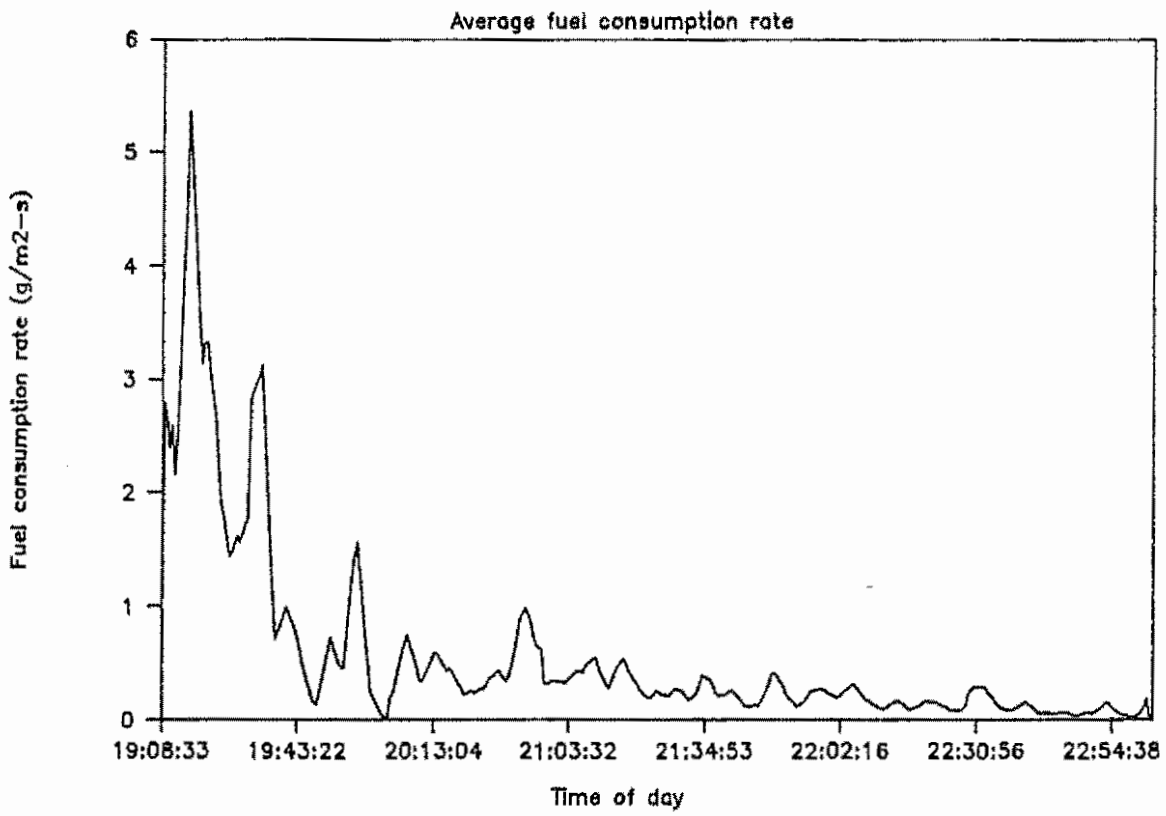
Rock Springs



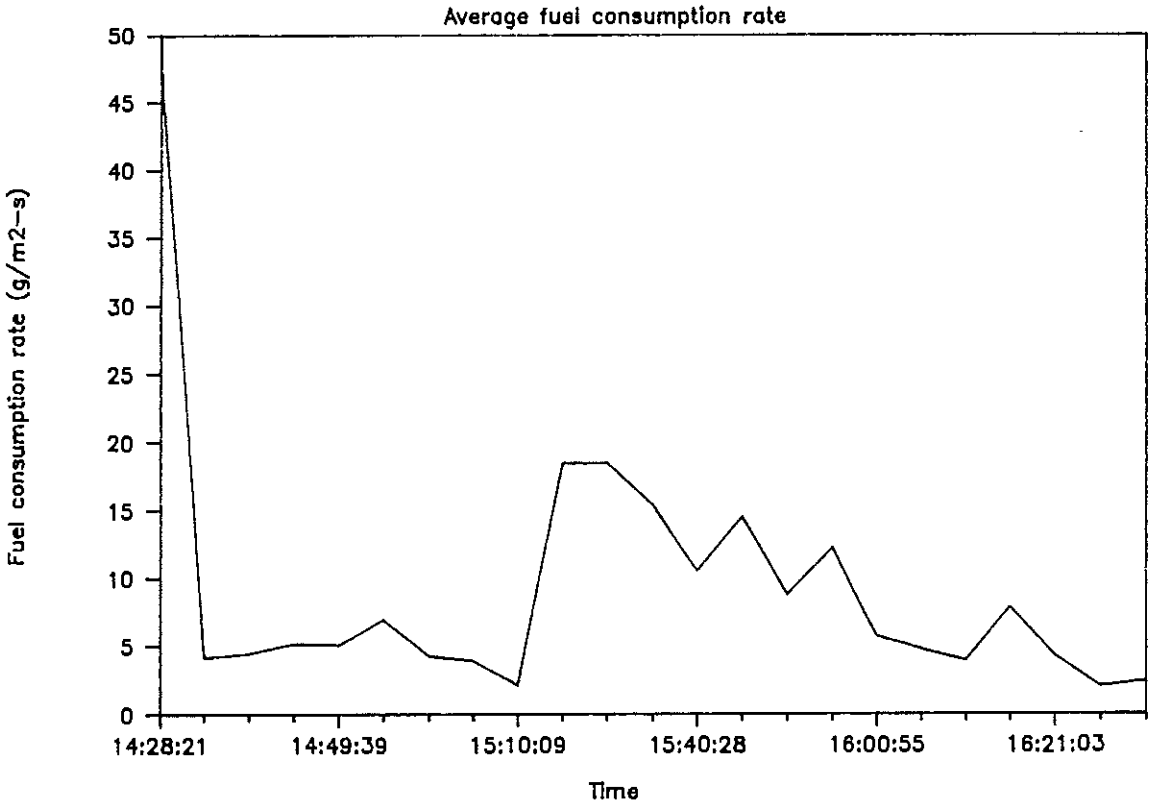
White Horse



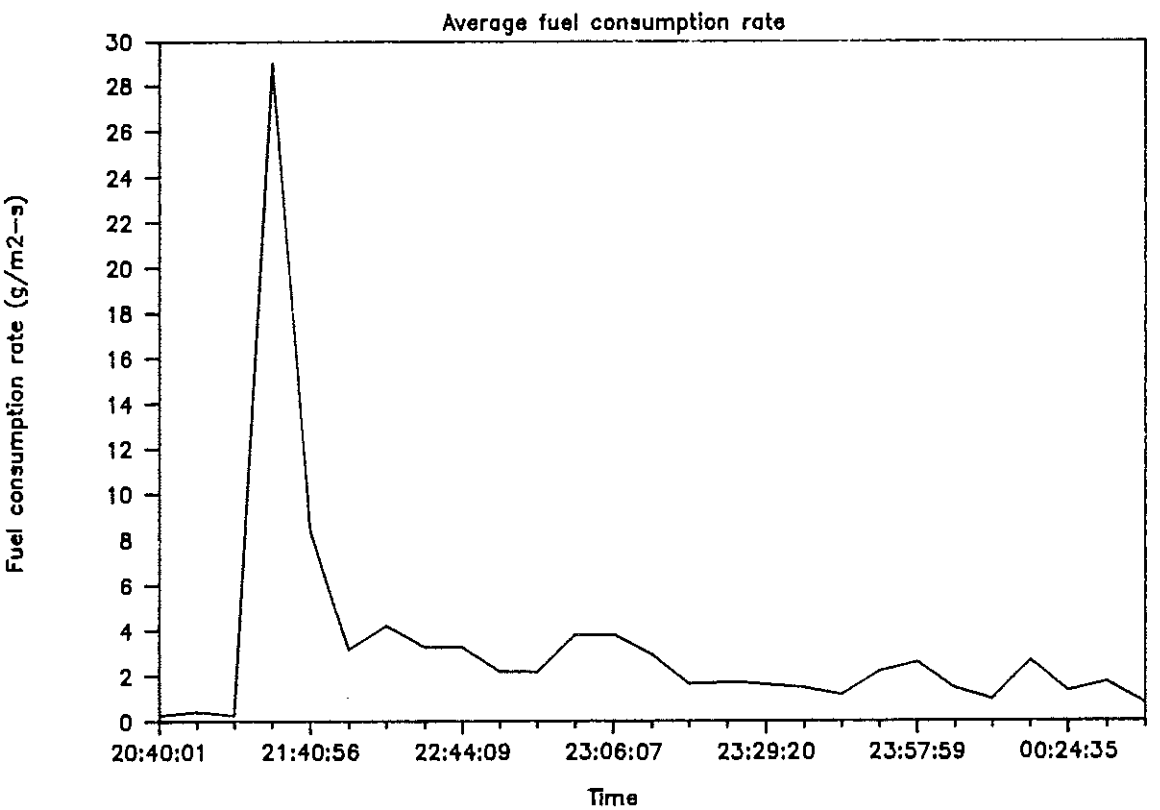
Hess



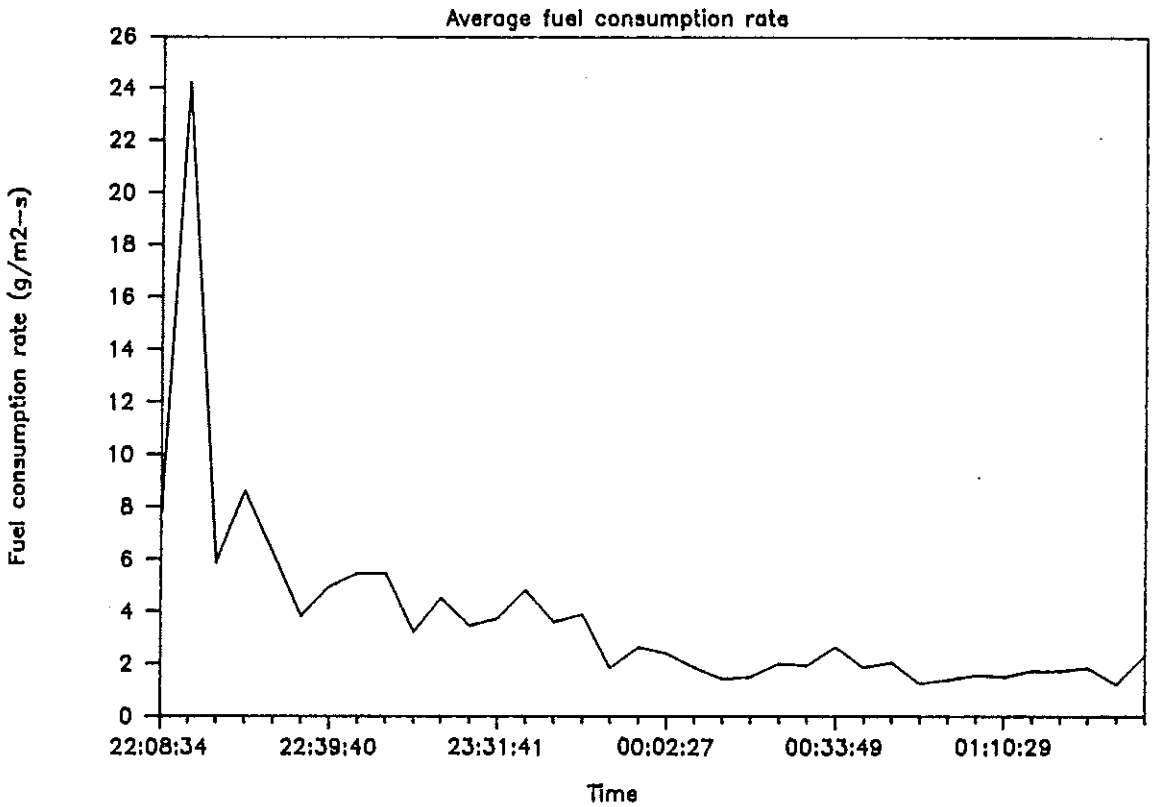
Pilchuck pile 1



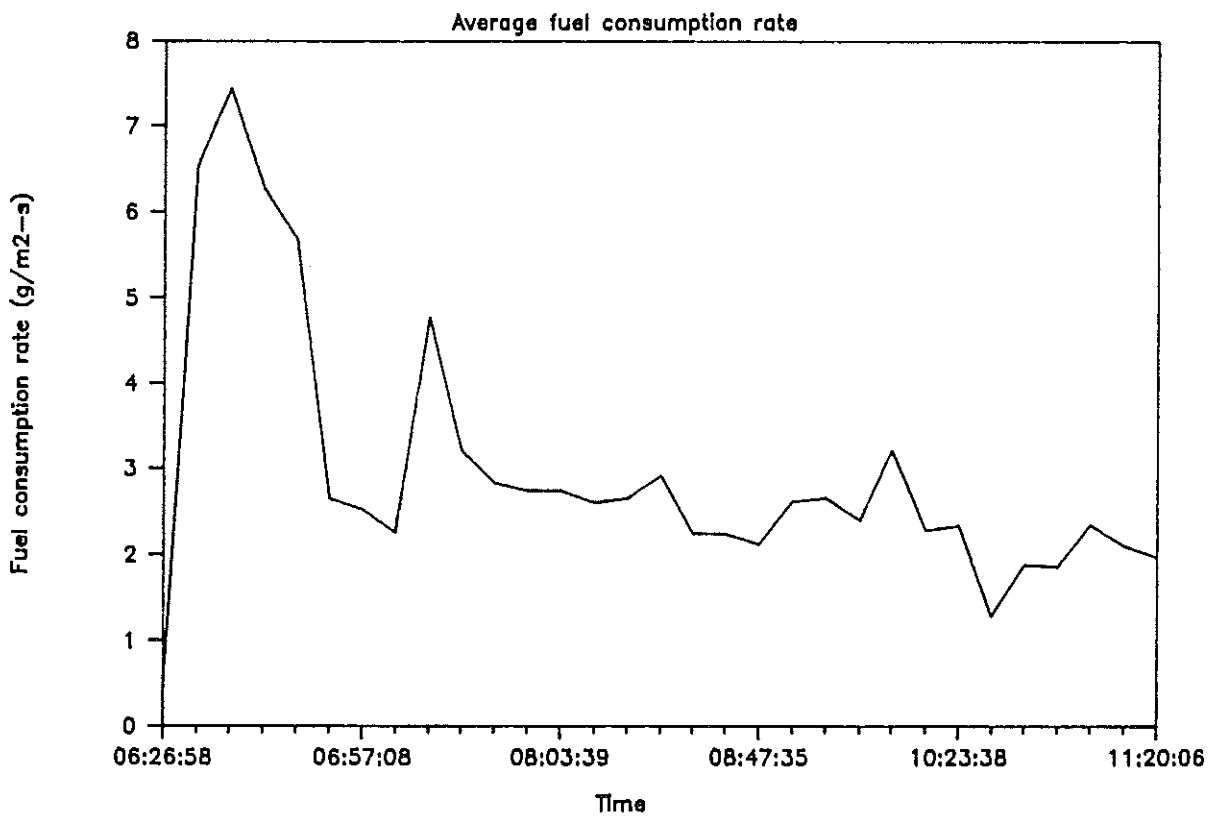
Pilchuck pile 2



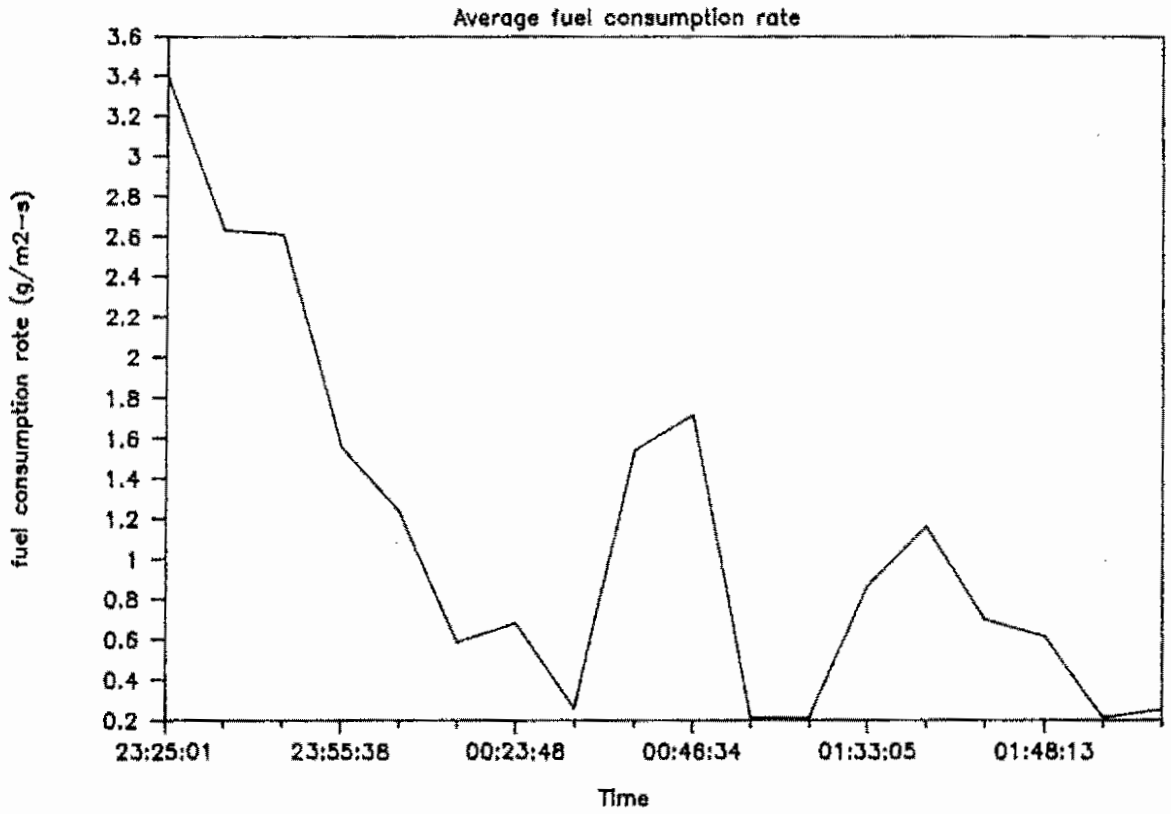
Pilchuck pile 3



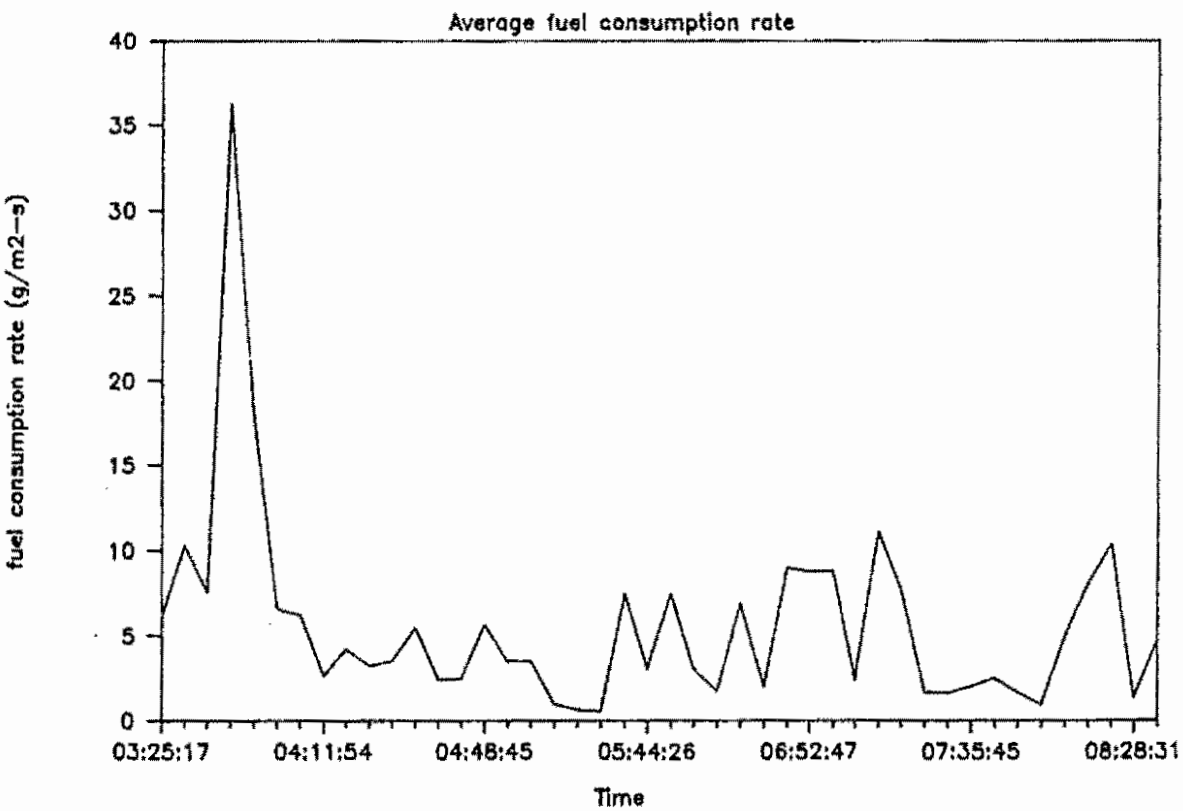
Pilchuck pile 4



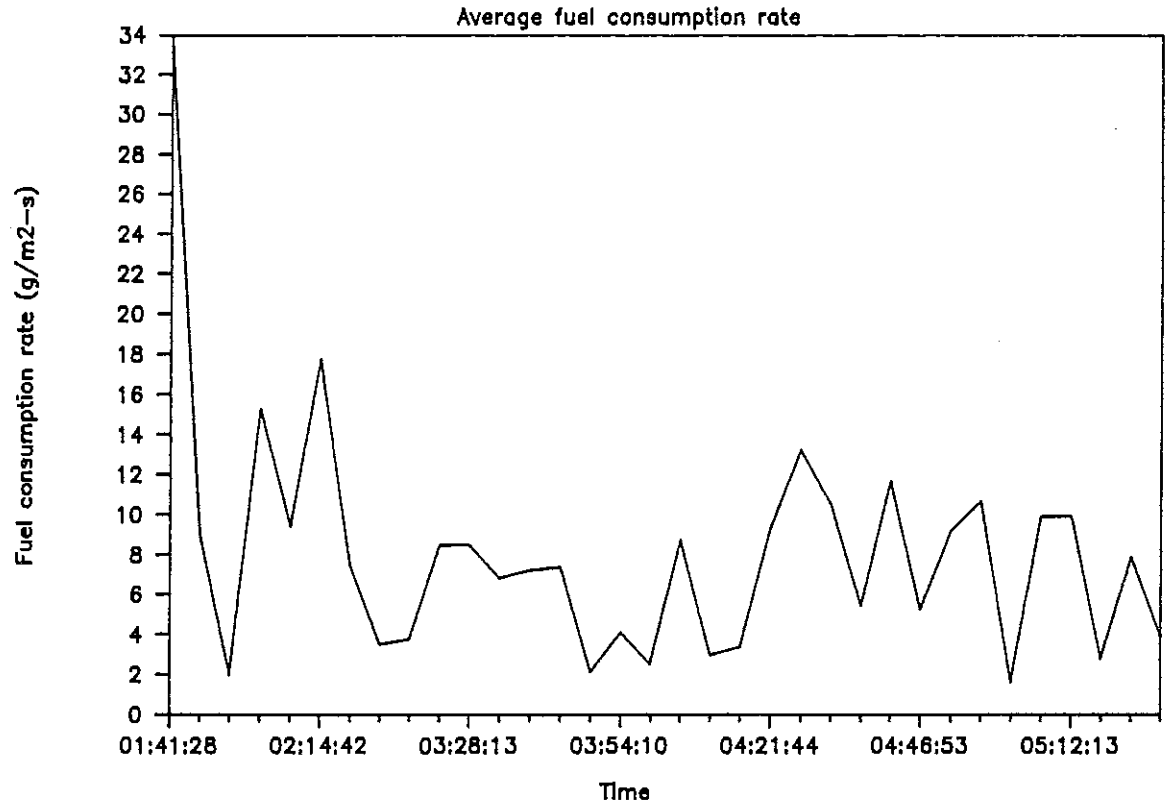
Skykomish pile 1



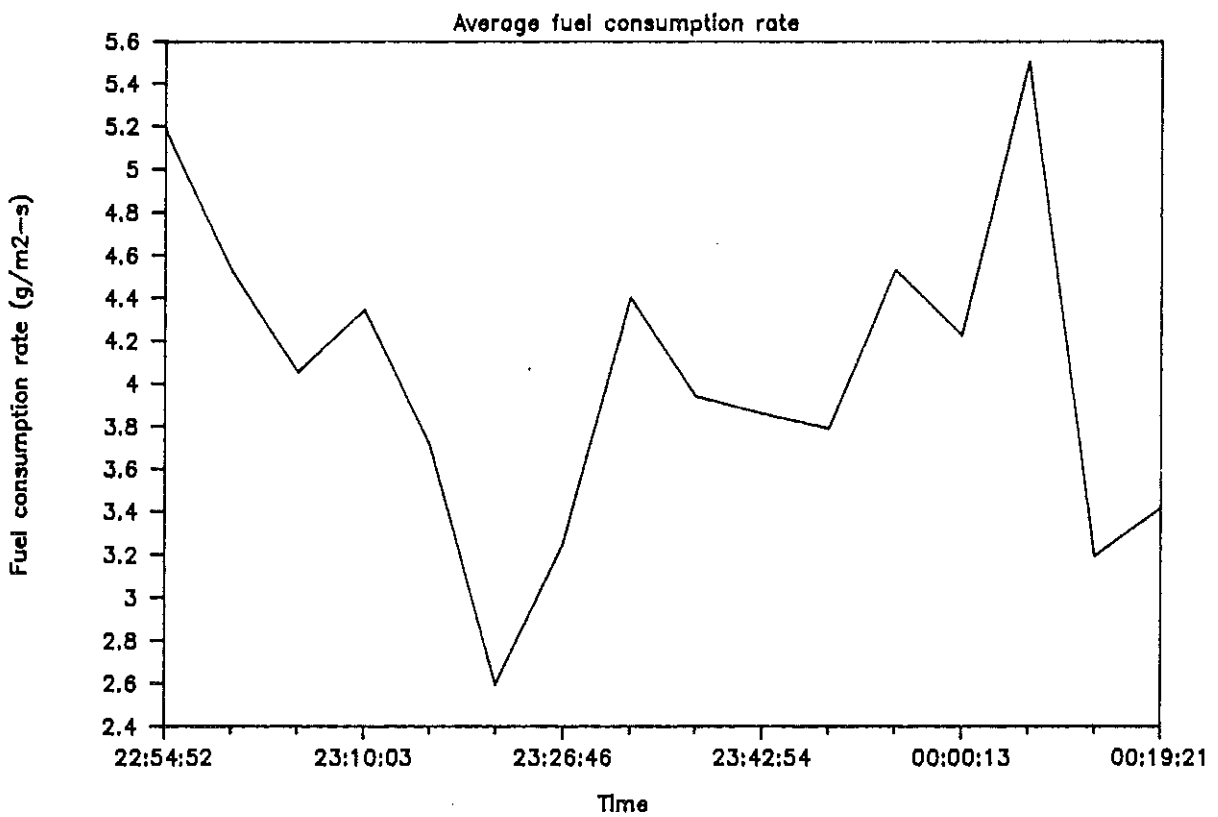
Skykomish pile 2



Skykomish pile 3



Skykomish pile 4



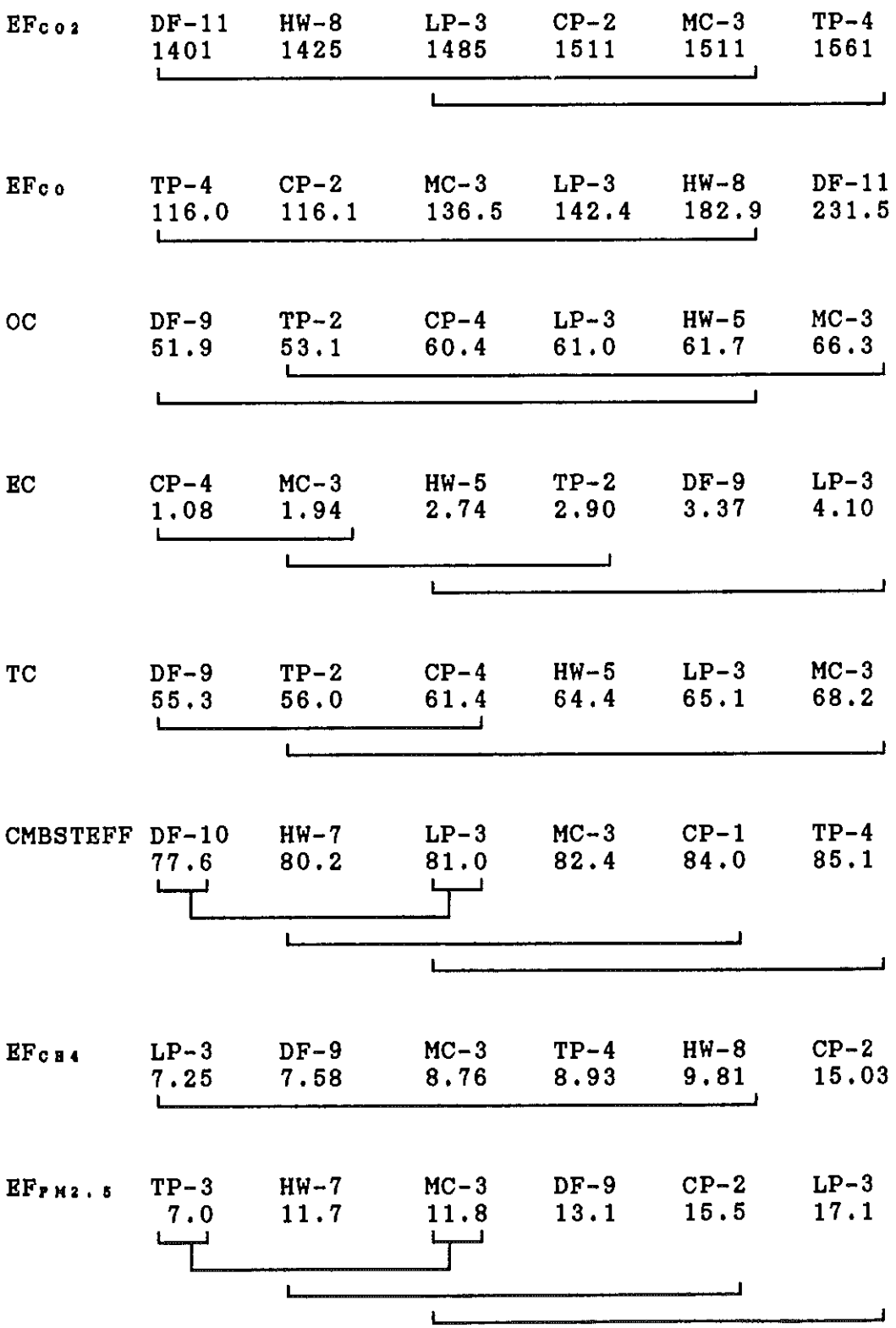
-- APPENDIX E --

Multiple Comparison of Means

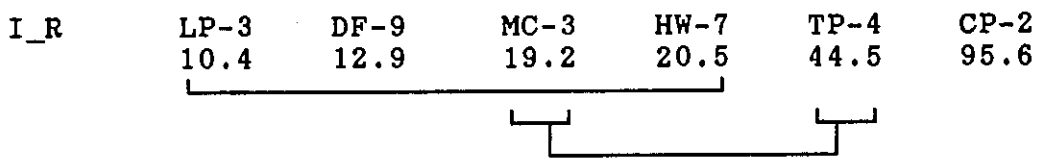
E.1.1. All Fuels - - Flaming Phase.

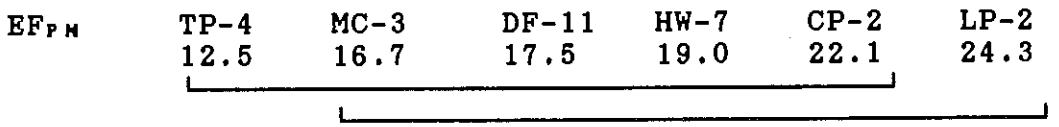
EF_{CO2}	CP-4	DF-10	HW-8	LP-3	MC-3	TP-4
	1674	1692	1694	1700	1728	1745
EF_{CO}	TP-4	MC-3	LP-3	HW-8	CP-4	DF-10
	22.1	26.4	44.5	45.7	50.3	71.5
OC	DF-8	TP-4	LP-4	MC-3	CP-4	HW-4
	36.4	49.0	55.1	57.7	59.8	60.3
EC	CP-4	TP-4	HW-4	LP-4	DF-8	MC-3
	2.30	8.18	8.28	10.90	18.62	18.43
TC	DF-8	TP-4	CP-4	LP-4	HW-4	MC-3
	55.0	57.2	62.1	66.0	68.6	86.1
EF_{CH4}	TP-4	MC-3	LP-3	HW-8	DF-9	CP-4
	1.23	1.46	1.47	2.15	2.27	4.78
EF_{NMHC}	TP-4	MC-3	LP-3	DF-9	HW-8	CP-4
	1.14	1.61	1.79	2.07	2.63	4.14
I_R	HW-8	DF-10	MC-3	LP-3	TP-4	CP-4
	54.5	62.1	62.5	126.0	128.8	143.9

E.1.2. All Fuels - - Smoldering Phase.

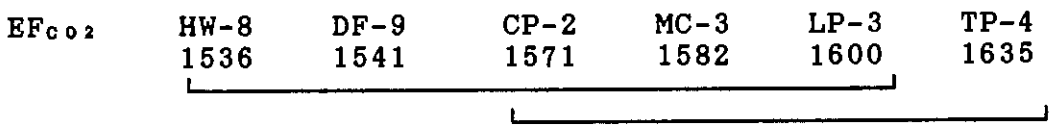


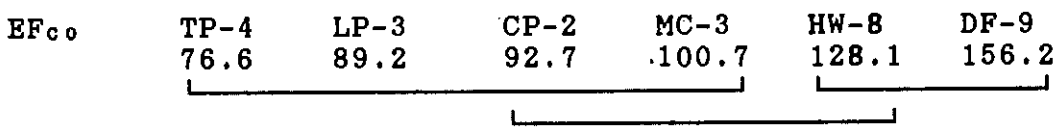
E.1.2. All Fuels - - Smoldering Phase (continued).

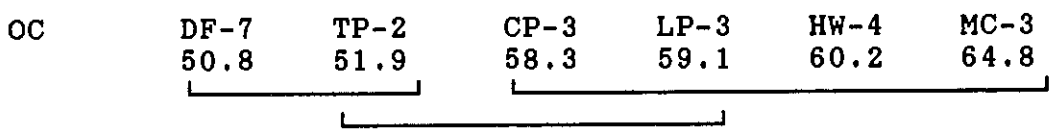


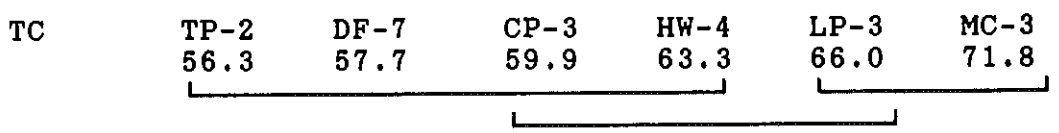


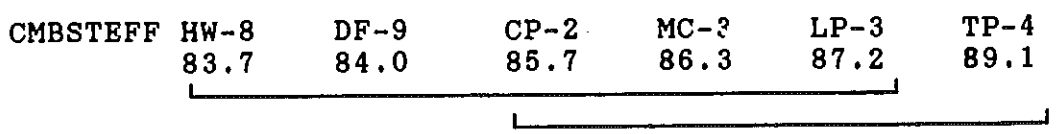
E.1.3. All Fuels - - Total Fire.

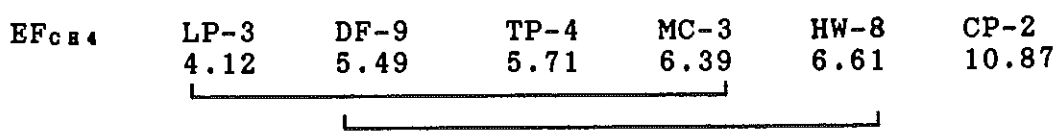




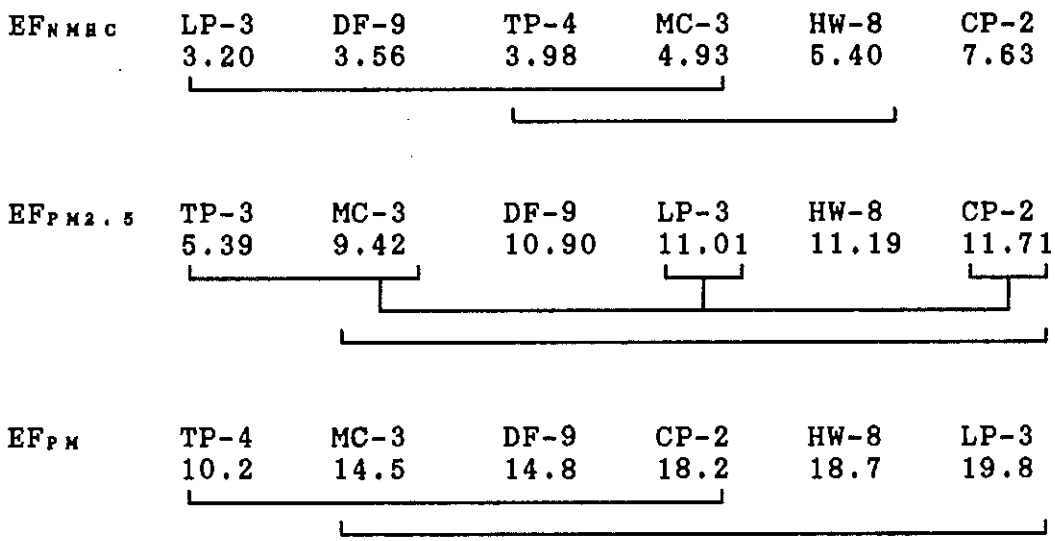




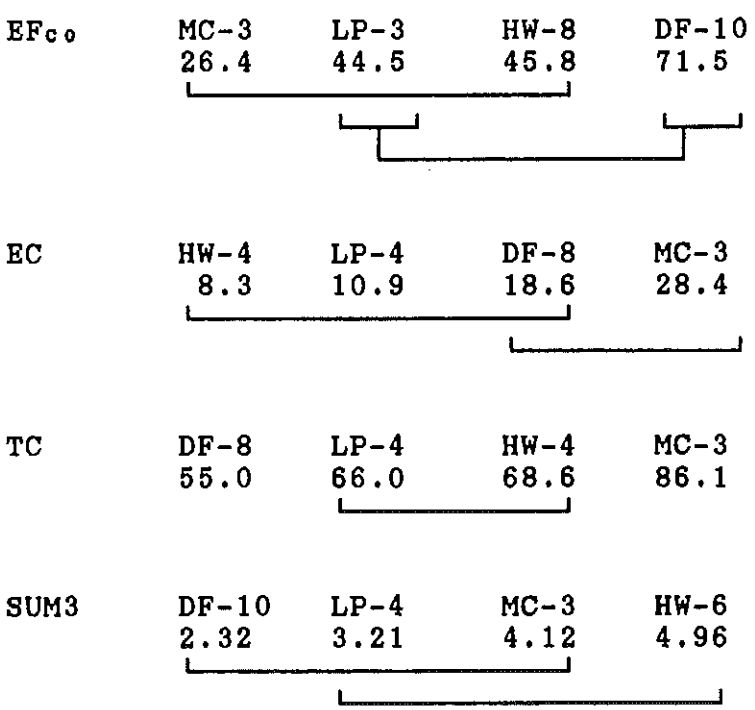




E.1.3. All Fuels - - Total Fire (continued).



E.2.1. Broadcast burns - - Flaming Phase.



E.2.2. Broadcast Burns - - Smoldering Phase.

EF_{CO}	MC-3	LP-3	HW-8	DF-11
	136.5	142.4	182.9	231.5

EC	MC-3	HW-5	DF-9	LP-3
	1.94	2.74	3.37	4.10

CMBSTEFF	DF-10	HW-7	LP-3	MC-3
	77.6	80.2	81.0	82.4

EF_{NMHC}	DF-9	LP-3	MC-3	HW-8
	4.45	4.83	6.58	7.00

$EF_{PM2.5}$	HW-7	MC-3	DF-9	LP-3
	11.7	11.8	13.1	17.1

SUM3	DF-11	MC-3	LP-3	HW-8
	.358	.489	.888	1.548

E.2.3. Broadcast Burns - - Total Fire.

EF_{CO}	LP-3	MC-3	HW-8	DF-9
	89.2	100.7	128.1	156.2

OC	DF-7	LP-3	HW-4	MC-3
	50.8	59.1	60.2	64.8

E.2.3. Broadcast Burns - - Total Fire (continued).

TC	DF-7	HW-4	LP-3	MC-3
	57.7	63.3	66.0	71.8
	└──────┘		└──────┘	
	└──────────┘			

EF_{CH_4}	LP-3	DF-9	MC-3	HW-8
	4.12	5.49	6.39	6.61
	└──────────┘			
	└──────────┘		└──────┘	

EF_{NMHC}	LP-2	DF-9	MC-3	HW-8
	3.20	3.56	4.93	5.40
	└──────────┘			
			└──────┘	

E.3.1. General Fuel Categories - - Flaming Phase.

I_R	HW-8	CO-16	LP-8
	54.5	74.2	136.3
	└──────┘		

E.3.2. General Fuel Categories - - Smoldering Phase

EF_{CO_2}	HW-8	CO-17	PI-6
	1425	1435	1544
	└──────┘		

EC	PI-6	HW-5	CO-15
	1.68	2.74	3.23
	└──────┘		
		└──────┘	

CMBSTEFF	CO-16	HW-7	PI-5
	79.1	80.2	84.9
	└──────┘		

EF_{CH_4}	CO-15	HW-8	PI-6
	7.75	9.81	10.96
	└──────┘		

E.3.2. General Fuel Categories - - Smoldering phase (continued).

EF_{NMHC}	CO-15	HW-8	PI-6
	4.96	7.00	7.45

E.3.3. General Fuel Categories - - Total Fire.

EF_{CO_2}	HW-8	CO-15	PI-6
	1536	1561	1614

EF_{CO}	PI-6	HW-8	CO-15
	81.9	128.1	131.7

EF_{NMHC}	CO-15	PI-6	HW-8
	3.76	5.19	5.40

-- APPENDIX F --

Correlation Matrices

F.1.1 All Fires -- Flaming (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
NA	1.00	-.05	-.05	.	-.45	-.57	-.57	-.15	-.06	-.11	-.11	.25	-.10	.22	.22	-.18	-.34	.	.	.	-.11	-.12	-.14	-.68
AL	-.05	1.00	.89**	.75**	.33	.17	.27	.09	.13	.12	.27	.46*	.88**	.97**	.93**	.17	.73**	.75**	.95**	.72**	.88**	-.26	.26	-.02
SI	-.05	.89**	1.00	.91**	.50*	.28	.41	.36	-.01	-.01	.13	.37	.76**	.87**	.84**	.44	.83**	.71**	.92**	.71**	.90**	.00	-.04	-.03
P	.	.75**	.91**	1.00	.46	.28	.42	.43	.79**	.51	.70**	.54*	.74**	.72**	.74**	.49	.72**	.52	.56**	.54	.82**	-.42	.71**	.42
S	-.45	.33	.50*	.46	1.00	.66**	.95**	.50*	-.09	-.01	-.03	.30	.17	.28	.18	.76**	.79**	.50	.28	.34	.47	.07	.06	.14
CL	-.57	.17	.28	.28	.66**	1.00	.68**	.02	-.16	-.09	-.10	-.01	.02	.08	.16	.28	.52*	.13	.06	.06	.11	.18	.05	.25
K	-.57	.27	.41	.42	.95**	.68**	1.00	.44	-.03	.05	.03	.38	.15	.20	.14	.72**	.74**	.44	.22	.20	.40	.01	.19	.20
CA	-.15	.09	.36	.43	.50*	.02	.44	1.00	.01	.02	-.02	.34	-.01	-.01	-.04	.87**	.40	.18	-.12	.27	.34	-.19	-.02	-.23
TI	-.06	.13	-.01	.79**	-.09	-.16	-.03	.01	1.00	.96**	.96**	.62**	.51*	.18	.21	.11	.07	.76**	.89**	.62*	.29	-.71**	.53*	-.26
V	-.11	.12	-.01	.51	-.01	-.09	.05	.02	.96**	1.00	.98**	.51*	.51*	.15	.18	.15	.06	.69**	.81**	.56*	.25	-.52*	.42	-.15
CR	-.11	.27	.13	.70**	-.03	-.10	.03	-.02	.96**	.98**	1.00	.57*	.65**	.30	.34	.11	.14	.71**	.96**	.65*	.37	-.54*	.45	-.15
MN	.25	.46*	.37	.54*	.30	-.01	.38	.34	.62**	.51*	.57*	1.00	.55*	.50*	.51*	.37	.55*	.85**	.63*	.62*	.63**	-.70**	.48	-.29
FE	-.10	.88**	.76**	.74**	.17	.02	.15	-.01	.51*	.51*	.65**	.55*	1.00	.91**	.90**	.11	.60**	.72**	.97**	.66**	.85**	-.53*	.44	-.14
NI	.22	.97**	.87**	.72**	.28	.08	.20	-.01	.18	.15	.30	.50*	.91**	1.00	.94**	.12	.73**	.77**	.98**	.71**	.91**	-.51	.26	-.31
CU	.22	.93**	.84**	.74**	.18	.16	.14	-.04	.21	.18	.34	.51*	.90**	.94**	1.00	.07	.68**	.77**	.92**	.74**	.84**	-.45	.27	-.24
ZN	-.18	.17	.44	.49	.76**	.28	.72**	.87**	.11	.15	.11	.37	.11	.12	.07	1.00	.57*	.32	.02	.43	.46	-.14	.17	.02
BR	-.34	.73**	.83**	.72**	.79**	.52*	.74**	.40	.07	.06	.14	.55*	.60**	.73**	.68**	.57*	1.00	.79**	.69**	.63*	.85**	-.21	.02	-.22
AG	.	.75**	.71**	.52	.50	.13	.44	.18	.76**	.69**	.71**	.85**	.72**	.77**	.77**	.32	.79**	1.00	.78**	.84**	.79**	-.63*	-.01	-.33
CD	.	.95**	.82**	.66**	.28	.06	.22	-.12	.89**	.81**	.96**	.63*	.97**	.98**	.92**	.02	.69**	.78**	1.00	.64*	.87**	-.42	.48	.21
SN	.	.72**	.71**	.54	.34	.06	.20	.27	.62*	.56*	.65*	.62*	.66**	.71**	.74**	.43	.63*	.84**	.64*	1.00	.73**	-.31	-.09	-.24
PB	-.11	.88**	.90**	.82**	.47	.11	.40	.34	.29	.25	.37	.63**	.85**	.91**	.84**	.46	.85**	.79**	.87**	.73**	1.00	-.49	.24	-.31
OC	-.12	-.26	.00	-.42	.07	.18	.01	-.19	-.71**	-.52*	-.54*	-.70**	-.53*	-.51	-.45	-.14	-.21	-.63*	-.42	-.31	-.49	1.00	-.56*	.54*
EC	-.14	.26	-.04	.71**	.06	.05	.19	-.02	.53*	.42	.45	.48	.44	.26	.27	.17	.02	-.01	.48	-.09	.24	-.56*	1.00	.39
TC	-.68	-.02	-.03	.42	.14	.25	.20	-.23	-.26	-.15	-.15	-.29	-.14	-.31	-.24	.02	-.22	-.33	.21	-.24	-.31	.54*	.39	1.00

2-tailed Signif: * - .01 ** - .001

F.1.2 All Fires -- Flaming (p.2 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.12	-.14	-.68	-.80	-.31	.46	.60	.29	-.31	.44	.68	-.81	-.79	-.79	-.62	-.68	-.81	-.66	-.65
AL	-.26	.26	-.02	-.11	.01	.25	.08	-.11	.01	-.22	.02	-.25	-.27	-.02	-.07	-.16	-.11	-.19	-.13
SI	.00	-.04	-.03	-.17	.10	.07	-.03	-.24	.11	-.32	-.09	-.21	-.17	-.17	-.17	-.26	-.17	-.26	-.20
P	-.42	.71**	.42	-.02	.19	.06	-.01	-.23	.19	-.43	-.26	-.36	-.26	.02	.02	-.14	-.01	-.23	-.18
S	.07	.06	.14	.02	.39	-.33	-.34	-.50*	.40	-.52*	-.40	-.10	.16	-.13	-.11	-.23	.03	-.20	-.12
CL	.18	.05	.25	.05	.06	-.08	-.01	-.14	.07	-.27	-.16	-.23	-.08	.01	.10	-.04	.05	.03	.10
K	.01	.19	.20	-.03	.42	-.38	-.38	-.54*	.44	-.49*	-.42	-.05	.16	-.20	-.17	-.28	-.02	-.24	-.19
CA	-.19	-.02	-.23	.04	.47*	-.42	-.36	-.39	.47*	-.42	-.48*	.01	.14	-.07	-.09	-.14	.05	-.19	-.19
TI	-.71**	.53*	-.26	.30	.40	-.23	-.33	-.04	.39	-.24	-.21	-.19	-.09	.12	-.04	.14	.32	-.00	.04
V	-.52*	.42	-.15	.26	.37	-.21	-.31	-.13	.36	-.24	-.19	-.13	-.06	.05	-.09	.06	.28	-.06	.01
CR	-.54*	.45	-.15	.22	.34	-.13	-.27	-.11	.33	-.23	-.15	-.16	-.11	.04	-.12	.05	.24	-.07	.01
MN	-.70**	.48	-.29	-.01	.57**	-.33	-.43	-.39	.56*	-.41	-.39	-.04	.05	-.17	-.26	-.20	.01	-.25	-.25
FE	-.53*	.44	-.14	-.06	.08	.15	-.00	-.10	.07	-.19	.04	-.20	-.23	-.10	-.16	-.14	-.05	-.19	-.11
NI	-.51	.26	-.31	-.12	-.09	.38	.21	-.01	-.09	-.14	.09	-.18	-.21	-.04	-.09	-.13	-.12	-.17	-.12
CU	-.45	.27	-.24	-.16	-.06	.33	.20	-.02	-.06	-.15	.08	-.16	-.23	-.11	-.13	-.14	-.16	-.17	-.12
ZN	-.14	.17	.02	-.01	.60*	-.50	-.47	-.68**	.61**	-.63**	-.67**	-.04	.15	-.17	-.14	-.28	.00	-.37	-.36
BR	-.21	.02	-.22	-.07	.20	-.06	-.11	-.30	.20	-.42	-.26	-.15	-.06	-.14	-.11	-.16	-.07	-.21	-.17
AG	-.63*	-.01	-.33	-.29	.21	.10	-.04	-.29	.21	-.35	-.24	-.00	.04	-.20	-.26	-.29	-.29	-.31	-.28
CD	-.42	.48	.21	-.17	-.16	.47	.29	.06	-.16	-.12	.12	-.20	-.22	.04	-.03	-.13	-.18	-.16	-.11
SN	-.31	-.09	-.24	-.19	.27	.11	-.03	-.37	.27	-.38	-.29	-.04	-.01	-.11	-.17	-.28	-.18	-.30	-.27
PB	-.49	.24	-.31	-.06	.15	.13	-.02	-.20	.15	-.33	-.15	-.17	-.10	-.05	-.12	-.15	-.05	-.23	-.19
OC	1.00	-.56*	.54*	-.26	-.32	.20	.16	-.11	-.33	.25	.33	.26	.15	-.21	-.14	-.23	-.28	-.06	.01
EC	-.56*	1.00	.39	.26	.47	-.29	-.35	-.24	.47	-.45	-.43	-.45	-.22	.11	-.03	.04	.27	-.02	-.00
TC	.54*	.39	1.00	-.04	.12	-.07	-.18	-.37	.12	-.18	-.07	-.17	-.06	-.12	-.19	-.21	-.03	-.08	.01

2-tailed Signif: * - .01 ** - .001

F.1.3 All Fires -- Flaming (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.12	-.26	.00	-.42	.07	.18	.01	-.19	-.71**	-.52*	-.54*	-.70**	-.53*	-.51	-.45	-.14	-.21	-.63*	-.42	-.31	-.49	1.00	-.56*	.54*
EC	-.14	.26	-.04	.71**	.06	.05	.19	-.02	.53*	.42	.45	.48	.44	.26	.27	.17	.02	-.01	.48	-.09	.24	-.56*	1.00	.39	
TC	-.68	-.02	-.03	.42	.14	.25	.20	-.23	-.26	-.15	-.15	-.29	-.14	-.31	-.24	.02	-.22	-.33	.21	-.24	-.31	.54*	.39	1.00	
CARBON	-.80	-.11	-.17	-.02	.02	.05	-.03	.04	.30	.26	.22	-.01	-.06	-.12	-.16	-.01	-.07	-.29	-.17	-.19	-.06	-.26	.26	-.04	
CMBSTEFF	-.31	.01	.10	.19	.39	.06	.42	.47*	.40	.37	.34	.57**	.08	-.09	-.06	.60*	.20	.21	-.16	.27	.15	-.32	.47	.12	
EFPM	.46	.25	.07	.06	-.33	-.08	-.38	-.42	-.23	-.21	-.13	-.33	.15	.38	.33	-.50	-.06	.10	.47	.11	.13	.20	-.29	-.07	
EFPM2.5	.60	.08	-.03	-.01	-.34	-.01	-.38	-.36	-.33	-.31	-.27	-.43	-.00	.21	.20	-.47	-.11	-.04	.29	-.03	-.02	.16	-.35	-.18	
EFCO	.29	-.11	-.24	-.23	-.50*	-.14	-.54*	-.39	-.04	-.13	-.11	-.39	-.10	-.01	-.02	-.68**	-.30	-.29	.06	-.37	-.20	-.11	-.24	-.37	
EFCO2	-.31	.01	.11	.19	.40	.07	.44	.47*	.39	.36	.33	.56*	.07	-.09	-.06	.61**	.20	.21	-.16	.27	.15	-.33	.47	.12	
EFCH4	.44	-.22	-.32	-.43	-.52*	-.27	-.49*	-.42	-.24	-.24	-.23	-.41	-.19	-.14	-.15	-.63**	-.42	-.35	-.12	-.38	-.33	.25	-.45	-.18	
EFNMHC	.68	.02	-.09	-.26	-.40	-.16	-.42	-.48*	-.21	-.19	-.15	-.39	.04	.09	.08	-.67**	-.26	-.24	.12	-.29	-.15	.33	-.43	-.07	
W_FLUX	-.81	-.25	-.21	-.36	-.10	-.23	-.05	.01	-.19	-.13	-.16	-.04	-.20	-.18	-.16	-.04	-.15	-.00	-.20	-.04	-.17	.26	-.45	-.17	
I_R	-.79	-.27	-.17	-.26	.16	-.08	.16	.14	-.09	-.06	-.11	.05	-.23	-.21	-.23	.15	-.06	.04	-.22	-.01	-.10	.15	-.22	-.06	
C_PM	-.79	-.02	-.17	.02	-.13	.01	-.20	-.07	.12	.05	.04	-.17	-.10	-.04	-.11	-.17	-.14	-.20	.04	-.11	-.05	-.21	.11	-.12	
C_PM2.5	-.62	-.07	-.17	.02	-.11	.10	-.17	-.09	-.04	-.09	-.12	-.26	-.16	-.09	-.13	-.14	-.11	-.26	-.03	-.17	-.12	-.14	-.03	-.19	
CO_PPM	-.68	-.16	-.26	-.14	-.23	-.04	-.28	-.14	.14	.06	.05	-.20	-.14	-.13	-.14	-.28	-.16	-.29	-.13	-.28	-.15	-.23	.04	-.21	
CO2_PPM	-.81	-.11	-.17	-.01	.03	.05	-.02	.05	.32	.28	.24	.01	-.05	-.12	-.16	.00	-.07	-.29	-.18	-.18	-.05	-.28	.27	-.03	
CH4_PPM	-.66	-.19	-.26	-.23	-.20	.03	-.24	-.19	-.00	-.06	-.07	-.25	-.19	-.17	-.17	-.37	-.21	-.31	-.16	-.30	-.23	-.06	-.02	-.08	
NMHC_PPM	-.65	-.13	-.20	-.18	-.12	.10	-.19	-.19	.04	.01	.01	-.25	-.11	-.12	-.12	-.36	-.17	-.28	-.11	-.27	-.19	.01	-.00	.01	

2-tailed Signif: * - .01 ** - .001

F.1.4 All Fires -- Flaming (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	-.56*	.54*	-.26	-.32	.20	.16	-.11	-.33	.25	.33	.26	.15	-.21	-.14	-.23	-.28	-.06	.01
EC	-.56*	1.00	.39	.26	.47	-.29	-.35	-.24	.47	-.45	-.43	-.45	-.22	.11	-.03	.04	.27	-.02	-.00
TC	.54*	.39	1.00	-.04	.12	-.07	-.18	-.37	.12	-.18	-.07	-.17	-.06	-.12	-.19	-.21	-.03	-.08	.01
CARBON	-.26	.26	-.04	1.00	.17	-.23	-.23	.13	.16	-.27	-.27	-.33	.05	.74**	.62**	.86**	.00**	.81**	.80**
CMBSTEFF	-.32	.47	.12	.17	1.00	-.84**	-.88**	-.86**	.00**	-.71**	-.70**	-.14	.11	-.29	-.41	-.24	.19	-.19	-.15
EFPM	.20	-.29	-.07	-.23	-.84**	1.00	.90**	.72**	-.83**	.49*	.54*	-.07	-.25	.39	.43	.13	-.25	.12	.10
EFPM2.5	.16	-.35	-.18	-.23	-.88**	.90**	1.00	.82**	-.87**	.46	.45	-.09	-.25	.37	.56*	.21	-.25	.14	.07
EFCO	-.11	-.24	-.37	.13	-.86**	.72**	.82**	1.00	-.86**	.53*	.47*	-.03	-.17	.55*	.64**	.56**	.11	.38	.31
EFCO2	-.33	.47	.12	.16	.00**	-.83**	-.87**	-.86**	1.00	-.70**	-.69**	-.14	.11	-.29	-.40	-.25	.19	-.19	-.15
EFCH4	.25	-.45	-.18	-.27	-.71**	.49*	.46	.53*	-.70**	1.00	.92**	.50*	.15	-.08	-.00	.01	-.28	.21	.16
EFNMHC	.33	-.43	-.07	-.27	-.70**	.54*	.45	.47*	-.69**	.92**	1.00	.30	-.04	-.09	-.05	-.04	-.28	.19	.22
W_FLUX	.26	-.45	-.17	-.33	-.14	-.07	-.09	-.03	-.14	.50*	.30	1.00	.79**	-.30	-.33	-.26	-.33	-.12	-.17
I_R	.15	-.22	-.06	.05	.11	-.25	-.25	-.17	.11	.15	-.04	.79**	1.00	-.04	-.10	-.02	.05	.12	.08
C_PM	-.21	.11	-.12	.74**	-.29	.39	.37	.55*	-.29	-.08	-.09	-.30	-.04	1.00	.91**	.86**	.73**	.79**	.79**
C_PM2.5	-.14	-.03	-.19	.62**	-.41	.43	.56*	.64**	-.40	-.00	-.05	-.33	-.10	.91**	1.00	.86**	.60**	.74**	.70**
CO_PPM	-.23	.04	-.21	.86**	-.24	.13	.21	.56**	-.25	.01	-.04	-.26	-.02	.86**	.86**	1.00	.85**	.89**	.83**
CO2_PPM	-.28	.27	-.03	.00**	.19	-.25	-.25	.11	.19	-.28	-.28	-.33	.05	.73**	.60**	.85**	1.00	.79**	.79**
CH4_PPM	-.06	-.02	-.08	.81**	-.19	.12	.14	.38	-.19	.21	.19	-.12	.12	.79**	.74**	.89**	.79**	1.00	.97**
NMHC_PPM	.01	-.00	.01	.80**	-.15	.10	.07	.31	-.15	.16	.22	-.17	.08	.79**	.70**	.83**	.79**	.97**	1.00

2-tailed Signif: * - .01 ** - .001

P.2.1 All Fires -- Smoldering (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
NA	1.00	.98*	.90	.	.69	.79	-.37	.53	.99**	-.11	.97*	.97*	.27	.85	.85	.77	.31	.	.	.	.95	-.76	.72	-.69
AL	.98*	1.00	.95**	.95**	.17	.40	.38	.84**	.09	.09	.13	.28	.86**	.06	.06	.61*	.22	.44	.86**	.88**	.26	-.30	.38	-.24
SI	.90	.95**	1.00	.94**	.11	.35	.46*	.90**	-.02	-.00	.03	.13	.89**	.05	-.03	.63**	.05	.26	.90**	.89**	.06	-.39	.26	-.35
P	.	.95**	.94**	1.00	.18	.56*	.57*	.86**	.65*	.43	.91**	.08	.86**	.10	.49	.66*	.34	.26	.83**	.81**	.29	.04	.59	.21
S	.69	.17	.11	.18	1.00	.61**	.04	-.04	-.14	-.17	-.15	-.20	.03	-.05	-.17	-.16	.21	.04	-.03	.10	-.14	.05	-.12	.03
CL	.79	.40	.35	.56*	.61**	1.00	.40	.16	-.22	-.24	-.17	-.04	.22	-.06	-.22	.15	.42	.03	.14	.17	-.09	-.01	.03	-.01
K	-.37	.38	.46*	.57*	.04	.40	1.00	.54*	-.34	-.30	-.26	-.04	.27	.06	-.26	.65**	-.25	-.12	.57*	.48	-.29	.10	-.22	.07
CA	.53	.84**	.90**	.86**	-.04	.16	.54*	1.00	.13	.13	.21	.20	.79**	.12	.17	.73**	-.10	.16	.95**	.89**	.12	-.41	.26	-.37
TI	.99**	.09	-.02	.65*	-.14	-.22	-.34	.13	1.00	.71**	.98**	.74**	.11	.14	.95**	.18	.50	.82**	.66*	.75**	.85**	-.36	.48	-.23
V	-.11	.09	-.00	.43	-.17	-.24	-.30	.13	.71**	1.00	.66**	.48	.07	.10	.74**	.17	.31	.86**	.57*	.65*	.69**	-.10	.39	.02
CR	.97*	.13	.03	.91**	-.15	-.17	-.26	.21	.98**	.66**	1.00	.74**	.15	.14	.96**	.25	.49	.22	.78**	.72**	.79**	-.36	.43	-.24
MN	.97*	.28	.13	.08	-.20	-.04	-.04	.20	.74**	.48	.74**	1.00	.37	.03	.73**	.14	.52*	.36	-.05	-.05	.76**	-.20	.27	-.16
FE	.27	.86**	.89**	.86**	.03	.22	.27	.79**	.11	.07	.15	.37	1.00	.02	.07	.58*	.15	.21	.75**	.76**	.11	-.42	.20	-.40
NI	.85	.06	.05	.10	-.05	-.06	.06	.12	.14	.10	.14	.03	.02	1.00	.12	.05	.08	-.07	.06	.04	.09	-.31	.52	-.17
CU	.85	.06	-.03	.49	-.17	-.22	-.26	.17	.95**	.74**	.96**	.73**	.07	.12	1.00	.23	.35	-.09	.42	.40	.77**	-.30	.38	-.19
ZN	.77	.61*	.63**	.66*	-.16	.15	.65**	.73**	.18	.17	.25	.14	.58*	.05	.23	1.00	-.08	.09	.70**	.69**	.21	-.24	.56*	-.08
BR	.31	.22	.05	.34	.21	.42	-.25	-.10	.50	.31	.49	.52*	.15	.08	.35	-.08	1.00	.45	-.04	.02	.59*	-.40	.49	-.26
AG	.	.44	.26	.26	.04	.03	-.12	.16	.82**	.86**	.22	.36	.21	-.07	-.09	.09	.45	1.00	.36	.49	.91**	.19	.37	.29
CD	.	.86**	.90**	.83**	-.03	.14	.57*	.95**	.66*	.57*	.78**	-.05	.75**	.06	.42	.70**	-.04	.36	1.00	.93**	.27	.08	.40	.19
SN	.	.88**	.89**	.81**	.10	.17	.48	.89**	.75**	.65*	.72**	-.05	.76**	.04	.40	.69**	.02	.49	.93**	1.00	.40	.22	.47	.35
PB	.95	.26	.06	.29	-.14	-.09	-.29	.12	.85**	.69**	.79**	.76**	.11	.09	.77**	.21	.59*	.91**	.27	.40	1.00	-.24	.63*	-.06
OC	-.76	-.30	-.39	.04	.05	-.01	.10	-.41	-.36	-.10	-.36	-.20	-.42	-.31	-.30	-.24	-.40	.19	.08	.22	-.24	1.00	-.20	.99**
EC	.72	.36	.26	.59	-.12	.03	-.22	.26	.48	.39	.43	.27	.20	.52	.38	.56*	.49	.37	.40	.47	.63*	-.20	1.00	-.04
TC	-.69	-.24	-.35	.21	.03	-.01	.07	-.37	-.23	.02	-.24	-.16	-.40	-.17	-.19	-.08	-.26	.29	.19	.35	-.06	.99**	-.04	1.00

2-tailed Signif: * - .01 ** - .001

F.2.2 All Fires -- Smoldering (p.2 of 4)

	OC	BC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_B	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.76	.72	-.69	-.79	-.47	-.88	-.80	.63	-.47	-.54	-.53	-.82	-.86	-.83	-.81	-.77	-.78	-.86	-.90
AL	-.30	.38	-.24	-.14	.06	-.19	-.07	-.02	.06	-.18	-.17	-.25	-.24	-.20	-.17	-.14	-.15	-.21	-.20
SI	-.39	.26	-.35	-.19	-.01	-.07	.03	.00	-.01	-.10	-.13	-.22	-.25	-.21	-.15	-.18	-.19	-.22	-.22
P	.04	.59	.21	.10	.02	-.15	-.16	.04	.02	-.25	-.24	-.28	-.26	.03	.01	.18	.11	-.01	.01
S	.05	-.12	.03	-.08	.14	-.10	-.23	-.16	.14	.03	.22	-.15	-.18	-.09	-.20	-.12	-.08	-.08	.01
CL	-.01	.03	-.01	.08	.17	.08	-.14	-.22	.17	-.13	.04	-.11	-.06	.16	-.01	-.04	.10	-.00	.11
K	.10	-.22	.07	-.09	.38	.01	-.07	-.49*	.38	.17	.19	.29	.27	-.06	-.17	-.23	-.06	-.06	-.03
CA	-.41	.26	-.37	-.08	.02	-.13	-.02	.01	.02	-.04	-.09	-.10	-.13	-.12	-.07	-.05	-.08	-.09	-.13
TI	-.36	.48	-.23	-.02	-.35	-.20	-.17	.60*	-.35	-.23	-.46	-.24	-.26	-.09	-.07	.17	-.06	-.08	-.20
V	-.10	.39	.02	.08	-.39	-.12	-.13	.59*	-.39	-.12	-.08	-.20	-.21	.02	.01	.49	.02	.06	.10
CR	-.36	.43	-.24	.08	-.34	-.20	-.17	.60*	-.34	-.25	-.49	-.22	-.23	.01	.04	.27	.04	.01	-.12
MN	-.20	.27	-.16	.08	-.07	-.26	-.17	.23	-.07	-.19	-.34	.06	.04	-.03	.05	.15	.08	.06	-.04
FE	-.42	.20	-.40	-.16	-.02	-.13	-.00	.08	-.02	-.22	-.28	-.22	-.28	-.20	-.09	-.12	-.16	-.21	-.25
NI	-.31	.52	-.17	.02	.18	-.31	-.33	-.04	.18	-.09	-.20	.29	.27	-.22	-.22	.00	.05	.01	-.08
CU	-.30	.38	-.19	.06	-.33	-.19	-.17	.58*	-.33	-.20	-.39	-.07	-.10	-.03	-.01	.42	.01	-.01	-.15
ZN	-.24	.56*	-.08	-.10	.15	.03	-.04	-.13	.15	-.28	-.42	-.14	-.13	.00	-.07	-.12	-.10	-.22	-.29
BR	-.40	.49	-.26	.26	-.16	-.16	-.24	.35	-.16	-.34	-.31	-.28	-.23	.16	.12	.45	.25	.09	.11
AG	.19	.37	.29	.20	.03	-.22	-.19	.04	.03	-.20	-.16	-.21	-.12	.03	.09	.29	.20	.16	.17
CD	.08	.40	.19	-.10	-.07	-.06	.02	.09	-.07	.02	-.02	-.16	-.14	-.14	-.08	-.04	-.11	-.08	-.11
SN	.22	.47	.35	-.06	.02	-.12	-.07	.01	.02	-.10	-.07	-.25	-.23	-.09	-.06	-.02	-.06	-.08	-.07
PB	-.24	.63*	-.06	.03	-.23	-.22	-.23	.45	-.23	-.32	-.47	-.24	-.20	-.05	-.05	.17	-.00	-.05	-.14
OC	1.00	-.20	.99**	.17	.21	.14	.16	-.36	.21	.47	.52*	-.08	.01	.23	.04	.08	.19	.30	.39
BC	-.20	1.00	-.04	-.07	-.17	.17	.11	.25	-.17	-.35	-.58*	-.61*	-.60*	-.02	-.07	.02	-.10	-.26	-.36
TC	.99**	-.04	1.00	.16	.19	.17	.19	-.32	.19	.42	.44	-.20	-.11	.23	.02	.08	.17	.26	.34

2-tailed Signif: * - .01 ** - .001

F.2.3 All Fires -- Smoldering (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.76	-.30	-.39	.04	.05	-.01	.10	-.41	-.36	-.10	-.36	-.20	-.42	-.31	-.30	-.24	-.40	.19	.08	.22	-.24	1.00	-.20	.99**
EC	.72	.38	.26	.59	-.12	.03	-.22	.26	.48	.39	.43	.27	.20	.52	.38	.56*	.49	.37	.40	.47	.63*	-.20	1.00	-.04
TC	-.69	-.24	-.35	.21	.03	-.01	.07	-.37	-.23	.02	-.24	-.16	-.40	-.17	-.19	-.08	-.26	.29	.19	.35	-.06	.99**	-.04	1.00
CARBON	-.79	-.14	-.19	.10	-.08	.08	-.09	-.08	-.02	.08	.08	.08	-.16	.02	.06	-.10	.26	.20	-.10	-.06	.03	.17	-.07	.16
CMBSTEFF	-.47	.06	-.01	.02	.14	.17	.38	.02	-.35	-.39	-.34	-.07	-.02	.18	-.33	.15	-.16	.03	-.07	.02	-.23	.21	-.17	.19
EFPM	-.88	-.19	-.07	-.15	-.10	.08	.01	-.13	-.20	-.12	-.20	-.26	-.13	-.31	-.19	.03	-.16	-.22	-.06	-.12	-.22	.14	.17	.17
EFPM2.5	-.80	-.07	.03	-.16	-.23	-.14	-.07	-.02	-.17	-.13	-.17	-.17	-.00	-.33	-.17	-.04	-.24	-.19	.02	-.07	-.23	.16	.11	.19
EFCO	.63	-.02	.00	.04	-.16	-.22	-.49*	.01	.60*	.59*	.60*	.23	.08	-.04	.58*	-.13	.35	.04	.09	.01	.45	-.36	.25	-.32
EFCO2	-.47	.06	-.01	.02	.14	.17	.38	.02	-.35	-.39	-.34	-.07	-.02	.18	-.33	.15	-.16	.03	-.07	.02	-.23	.21	-.17	.19
EFCH4	-.54	-.18	-.10	-.25	.03	-.13	.17	-.04	-.23	-.12	-.25	-.19	-.22	-.09	-.20	-.28	-.34	-.20	.02	-.10	-.32	.47	-.35	.42
EFNMHC	-.53	-.17	-.13	-.24	.22	.04	.19	-.09	-.46	-.08	-.49	-.34	-.28	-.20	-.39	-.42	-.31	-.16	-.02	-.07	-.47	.52*	-.58*	.44
W_FLUX	-.82	-.25	-.22	-.28	-.15	-.11	.29	-.10	-.24	-.20	-.22	.06	-.22	.29	-.07	-.14	-.28	-.21	-.16	-.25	-.24	-.08	-.61*	-.20
I_R	-.86	-.24	-.25	-.26	-.18	-.06	.27	-.13	-.26	-.21	-.23	.04	-.28	.27	-.10	-.13	-.23	-.12	-.14	-.23	-.20	.01	-.60*	-.11
C_PM	-.83	-.20	-.21	.03	-.09	.16	-.06	-.12	-.09	.02	.01	-.03	-.20	-.22	-.03	.00	.16	.03	-.14	-.09	-.05	.23	-.02	.23
C_PM2.5	-.81	-.17	-.15	.01	-.20	-.01	-.17	-.07	-.07	.01	.04	.05	-.09	-.22	-.01	-.07	.12	.09	-.08	-.06	-.05	.04	-.07	.02
CO_PPM	-.77	-.14	-.18	.18	-.12	-.04	-.23	-.05	.17	.49	.27	.15	-.12	.00	.42	-.12	.45	.29	-.04	-.02	.17	.08	.02	.08
CO2_PPM	-.78	-.15	-.19	.11	-.08	.10	-.06	-.08	-.06	.02	.04	.08	-.16	.05	.01	-.10	.25	.20	-.11	-.06	-.00	.19	-.10	.17
CH4_PPM	-.86	-.21	-.22	-.01	-.08	-.00	-.06	-.09	-.08	.06	.01	.06	-.21	.01	-.01	-.22	.09	.16	-.08	-.08	-.05	.30	-.26	.26
NMHC_PPM	-.90	-.20	-.22	.01	.01	.11	-.03	-.13	-.20	.10	-.12	-.04	-.25	-.08	-.15	-.29	.11	.17	-.11	-.07	-.14	.39	-.36	.34

2-tailed Signif: * - .01 ** - .001

P.2.4 All Fires -- Smoldering (p.4 of 4)

	OC	BC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	-.20	.99**	.17	.21	.14	.16	-.36	.21	.47	.52*	-.08	.01	.23	.04	.08	.19	.30	.39
BC	-.20	1.00	-.04	-.07	-.17	.17	.11	.25	-.17	-.35	-.58*	-.61*	-.60*	-.02	-.07	.02	-.10	-.26	-.36
TC	.99**	-.04	1.00	.16	.19	.17	.19	-.32	.19	.42	.44	-.20	-.11	.23	.02	.08	.17	.26	.34
CARBON	.17	-.07	.16	1.00	.16	-.18	-.16	-.05	.16	-.14	-.08	.04	.10	.92**	.92**	.95**	.00**	.95**	.88**
CMBSTEFF	.21	-.17	.19	.16	1.00	-.61**	-.69**	-.94**	1.00**	-.12	.12	.34	.33	.08	-.04	-.04	.20	.21	.22
EFPM	.14	.17	.17	-.18	-.61**	1.00	.90**	.36	-.61**	.37	.16	-.14	-.14	.11	.04	-.14	-.20	-.20	-.18
EFPM2.5	.16	.11	.19	-.16	-.69**	.90**	1.00	.44	-.69**	.54*	.19	-.13	-.15	.09	.08	-.09	-.18	-.14	-.16
EFCO	-.36	.25	-.32	-.05	-.94**	.36	.44	1.00	-.94**	-.11	-.32	-.43	-.41	-.03	.14	.19	-.09	-.14	-.19
EFCO2	.21	-.17	.19	.16	1.00**	-.61**	-.69**	-.94**	1.00	-.12	.12	.34	.33	.08	-.04	-.04	.20	.21	.22
EFCH4	.47	-.35	.42	-.14	-.12	.37	.54*	-.11	-.12	1.00	.72**	.44	.41	-.11	-.22	-.17	-.13	.11	.10
EFNMHC	.52*	-.58*	.44	-.08	.12	.16	.19	-.32	.12	.72**	1.00	.42	.37	-.02	-.15	-.15	-.07	.15	.36
W_FLUX	-.08	-.61*	-.20	.04	.34	-.14	-.13	-.43	.34	.44	.42	1.00	.95**	.01	-.02	-.06	.06	.24	.20
I_R	.01	-.60*	-.11	.10	.33	-.14	-.15	-.41	.33	.41	.37	.95**	1.00	.07	-.02	-.02	.12	.29	.24
C_PM	.23	-.02	.23	.92**	.08	.11	.09	-.03	.08	-.11	-.02	.01	.07	1.00	.95**	.87**	.91**	.86**	.82**
C_PM2.5	.04	-.07	.02	.92**	-.04	.04	.08	.14	-.04	-.22	-.15	-.02	-.02	.95**	1.00	.91**	.91**	.86**	.79**
CO_PPM	.08	.02	.08	.95**	-.04	-.14	-.09	.19	-.04	-.17	-.15	-.06	-.02	.87**	.91**	1.00	.93**	.88**	.78**
CO2_PPM	.19	-.10	.17	.00**	.20	-.20	-.18	-.09	.20	-.13	-.07	.06	.12	.91**	.91**	.93**	1.00	.95**	.88**
CH4_PPM	.30	-.26	.26	.95**	.21	-.20	-.14	-.14	.21	.11	.15	.24	.29	.86**	.86**	.88**	.95**	1.00	.93**
NMHC_PPM	.39	-.36	.34	.88**	.22	-.18	-.16	-.19	.22	.10	.36	.20	.24	.82**	.79**	.78**	.88**	.93**	1.00

2-tailed Signif: * - .01 ** - .001

F.3.1 All Fires -- Flaming and Smoldering (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
NA	1.00	.15	.08	.	-.01	-.05	-.07	-.09	.11	-.02	.05	.42	.03	.20	.20	.09	-.02	.	.	.	.16	-.41	.25	-.67
AL	.15	1.00	.88**	.77**	.30	.24	.30	.30	.14	.13	.27	.44**	.87**	.79**	.84**	.22	.66**	.71**	.93**	.74**	.80**	-.32	.28	-.08
SI	.08	.88**	1.00	.85**	.30	.24	.30	.55**	.00	.01	.12	.28	.78**	.60**	.63**	.36*	.62**	.57**	.77**	.70**	.68**	-.18	.06	-.15
P	.	.77**	.85**	1.00	.43*	.40*	.51**	.53**	.77**	.52**	.69**	.54**	.73**	.61**	.73**	.56**	.72**	.54**	.69**	.60**	.80**	-.46*	.78**	.44*
S	-.01	.30	.30	.43*	1.00	.68**	.75**	.31	-.04	.02	.04	.27	.11	.19	.18	.64**	.67**	.44*	.24	.33	.41*	-.10	.26	.15
CL	-.05	.24	.24	.40*	.68**	1.00	.76**	.12	-.09	-.03	-.01	.16	.05	.09	.21	.46**	.61**	.26	.14	.18	.22	-.07	.33	.25
K	-.07	.30	.30	.51**	.75**	.76**	1.00	.42**	.03	.10	.12	.45**	.14	.20	.22	.81**	.76**	.50**	.30	.33	.46**	-.22	.47**	.23
CA	-.09	.30	.55**	.53**	.31	.12	.42**	1.00	.06	.06	.03	.35*	.21	.04	.03	.71**	.37*	.21	.11	.40*	.33	-.31	.17	-.18
TI	.11	.14	.00	.77**	-.04	-.09	.03	.06	1.00	.91**	.91**	.63**	.44**	.18	.28	.14	.13	.75**	.85**	.65**	.34	-.63**	.47*	-.24
V	-.02	.13	.01	.52**	.02	-.03	.10	.06	.91**	1.00	.96**	.50**	.46**	.15	.22	.19	.12	.69**	.75**	.58**	.29	-.48**	.41*	-.12
CR	.05	.27	.12	.69**	.04	-.01	.12	.03	.91**	.96**	1.00	.57**	.60**	.28	.38*	.18	.20	.70**	.94**	.65**	.41*	-.52**	.44*	-.13
MN	.42	.44**	.28	.54**	.27	.16	.45**	.35*	.63**	.50**	.57**	1.00	.48**	.41*	.54**	.47**	.60**	.82**	.55**	.58**	.66**	-.63**	.53**	-.18
FE	.03	.87**	.78**	.73**	.11	.05	.14	.21	.44**	.46**	.60**	.48**	1.00	.73**	.81**	.14	.53**	.64**	.92**	.66**	.76**	-.44*	.26	-.24
NI	.20	.79**	.60**	.61**	.19	.09	.20	.04	.18	.15	.28	.41*	.73**	1.00	.82**	.14	.61**	.66**	.83**	.60**	.78**	-.50**	.32	-.26
CU	.20	.84**	.63**	.73**	.18	.21	.22	.03	.28	.22	.38*	.54**	.81**	.82**	1.00	.18	.68**	.77**	.88**	.72**	.84**	-.45*	.31	-.20
ZN	.09	.22	.36*	.56**	.64**	.46**	.81**	.71**	.14	.19	.18	.47**	.14	.14	.18	1.00	.66**	.42*	.12	.48*	.54**	-.34	.42*	.07
BR	-.02	.66**	.62**	.72**	.67**	.61**	.76**	.37*	.13	.12	.20	.60**	.53**	.61**	.68**	.66**	1.00	.79**	.64**	.63**	.86**	-.36	.26	-.15
AG	.	.71**	.57**	.54**	.44*	.26	.50**	.21	.75**	.69**	.70**	.82**	.64**	.66**	.77**	.42*	.79**	1.00	.75**	.83**	.81**	-.50*	.15	-.19
CD	.	.93**	.77**	.69**	.24	.14	.30	.11	.85**	.75**	.94**	.55**	.92**	.83**	.88**	.12	.64**	.75**	1.00	.67**	.83**	-.39	.54**	.26
SN	.	.74**	.70**	.60**	.33	.18	.33	.40*	.65**	.58**	.65**	.58**	.66**	.60**	.72**	.48*	.63**	.83**	.67**	1.00	.73**	-.30	.07	-.13
PB	.16	.80**	.68**	.80**	.41*	.22	.46**	.33	.34	.29	.41*	.66**	.76**	.78**	.84**	.54**	.86**	.81**	.83**	.73**	1.00	-.53**	.37	-.23
OC	-.41	-.32	-.18	-.46*	-.10	-.07	-.22	-.31	-.63**	-.48**	-.52**	-.63**	-.44*	-.50**	-.45*	-.34	-.36	-.50*	-.39	-.30	-.53**	1.00	-.58**	.56**
EC	.25	.28	.06	.78**	.26	.33	.47**	.17	.47*	.41*	.44*	.53**	.26	.32	.31	.42*	.26	.15	.54**	.07	.37	-.58**	1.00	.35
TC	-.67	-.08	-.15	.44*	.15	.25	.23	-.18	-.24	-.12	-.13	-.18	-.24	-.26	-.20	.07	-.15	-.19	.26	-.13	-.23	.56**	.35	1.00

2-tailed Signif: * - .01 ** - .001

F.3.2 All Fires -- Flaming and Smoldering (p.2 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.41	.25	-.67	-.27	.34	-.25	-.24	-.34	.34	-.32	-.15	-.57	-.16	-.46	-.44	-.52	-.24	-.52	-.43
AL	-.32	.28	-.08	-.01	.12	-.04	-.08	-.13	.12	-.20	-.13	-.24	-.15	-.01	-.06	-.14	-.01	-.20	-.13
SI	-.18	.06	-.15	-.09	.05	-.05	-.04	-.07	.05	-.14	-.12	-.22	-.12	-.15	-.14	-.22	-.10	-.25	-.19
P	-.46*	.78**	.44*	.17	.30	-.20	-.25	-.30	.30	-.40	-.38	-.30	-.06	.08	.05	-.11	.17	-.24	-.13
S	-.10	.26	.15	.26	.47**	-.35*	-.45**	-.48**	.47**	-.42**	-.31	-.17	.27	.07	-.03	-.14	.26	-.17	.00
CL	-.07	.33	.25	.33*	.45**	-.25	-.33	-.46**	.45**	-.48**	-.39*	-.20	.20	.21	.17	-.01	.33*	-.03	.16
K	-.22	.47**	.23	.35*	.65**	-.43**	-.54**	-.66**	.65**	-.59**	-.54**	-.06	.44**	.13	.02	-.15	.37*	-.20	-.02
CA	-.31	.17	-.18	.13	.26	-.30	-.27	-.23	.26	-.26	-.31	-.07	.17	.00	-.03	-.10	.14	-.17	-.14
TI	-.63**	.47*	-.24	.28	.09	-.21	-.22	.05	.09	-.19	-.25	-.18	-.01	.09	-.04	.14	.29	-.04	-.01
V	-.48**	.41*	-.12	.28	.13	-.16	-.20	-.04	.12	-.17	-.17	-.13	.01	.08	-.05	.11	.29	-.06	.04
CR	-.52**	.44*	-.13	.27	.18	-.16	-.21	-.11	.18	-.21	-.21	-.13	-.00	.07	-.07	.04	.28	-.08	.01
MN	-.63**	.53**	-.18	.21	.39*	-.39*	-.45**	-.31	.39*	-.43**	-.47**	-.06	.24	.03	-.07	-.07	.23	-.17	-.13
FE	-.44*	.26	-.24	-.04	.03	-.01	-.03	-.01	.02	-.12	-.09	-.20	-.19	-.11	-.13	-.13	-.04	-.19	-.14
NI	-.50**	.32	-.26	-.03	.10	-.07	-.12	-.09	.10	-.13	-.09	-.00	-.06	-.05	-.09	-.10	-.03	-.14	-.10
CU	-.45*	.31	-.20	-.00	.15	-.06	-.13	-.13	.14	-.24	-.18	-.14	-.06	-.02	-.07	-.08	-.00	-.17	-.09
ZN	-.34	.42*	.07	.30	.58**	-.46*	-.51**	-.56**	.58**	-.60**	-.64**	-.10	.39*	.05	.00	-.21	.31	-.34	-.21
BR	-.36	.26	-.15	.21	.41*	-.30	-.35	-.40*	.41*	-.49**	-.45*	-.16	.18	.04	.00	-.10	.21	-.21	-.08
AG	-.50*	.15	-.19	-.04	.29	-.19	-.25	-.30	.29	-.35	-.34	-.07	.17	-.08	-.15	-.22	-.04	-.28	-.21
CD	-.39	.54**	.26	-.05	.09	.03	-.03	-.11	.09	-.16	-.09	-.17	-.10	.04	-.02	-.12	-.05	-.17	-.10
SN	-.30	.07	-.13	-.00	.26	-.15	-.20	-.27	.26	-.31	-.31	-.11	.10	-.04	-.11	-.24	-.00	-.29	-.22
PB	-.53**	.37	-.23	.13	.28	-.20	-.27	-.26	.28	-.37*	-.34	-.17	.09	.03	-.06	-.11	.14	-.23	-.15
OC	1.00	-.58**	.56**	-.35	-.29	.33	.38*	.16	-.29	.45**	.49**	.14	-.11	-.19	-.16	-.11	-.36	.08	.05
EC	-.58**	1.00	.35	.48**	.55**	-.39*	-.48**	-.48**	.55**	-.55**	-.55**	-.32	.15	.25	.07	.03	.50**	-.06	.07
TC	.56**	.35	1.00	.08	.22	-.00	-.07	-.30	.22	-.04	.01	-.18	.03	.02	-.11	-.10	.09	.03	.12

2-tailed Signif: * - .01 ** - .001

F.3.3 All Fires -- Flaming and Smoldering (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.41	-.32	-.18	-.46*	-.10	-.07	-.22	-.31	-.63**	-.48**	-.52**	-.63**	-.44*	-.50**	-.45*	-.34	-.36	-.50*	-.39	-.30	-.53**	1.00	-.58**	.56**
EC	.25	.28	.06	.78**	.26	.33	.47**	.17	.47*	.41*	.44*	.53**	.26	.32	.31	.42*	.26	.15	.54**	.07	.37	-.58**	1.00	.35
TC	-.67	-.08	-.15	.44*	.15	.25	.23	-.18	-.24	-.12	-.13	-.18	-.24	-.26	-.20	.07	-.15	-.19	.26	-.13	-.23	.56**	.35	1.00
CARBON	-.27	-.01	-.09	.17	.26	.33*	.35*	.13	.28	.28	.27	.21	-.04	-.03	-.00	.30	.21	-.04	-.05	-.00	.13	-.35	.48**	.08
CMBSTEFF	.34	.12	.05	.30	.47**	.45**	.65**	.26	.09	.13	.18	.39*	.03	.10	.15	.58**	.41*	.29	.09	.26	.28	-.29	.55**	.22
EFPM	-.25	-.04	-.05	-.20	-.35*	-.25	-.43**	-.30	-.21	-.16	-.16	-.39*	-.01	-.07	-.06	-.46*	-.30	-.19	.03	-.15	-.20	.33	-.39*	-.00
EFPM2.5	-.24	-.08	-.04	-.25	-.45**	-.33	-.54**	-.27	-.22	-.20	-.21	-.45**	-.03	-.12	-.13	-.51**	-.35	-.25	-.03	-.20	-.27	.38*	-.48**	-.07
EFCO	-.34	-.13	-.07	-.30	-.48**	-.46**	-.66**	-.23	.05	-.04	-.11	-.31	-.01	-.09	-.13	-.56**	-.40*	-.30	-.11	-.27	-.26	.16	-.48**	-.30
EFCO2	.34	.12	.05	.30	.47**	.45**	.65**	.26	.09	.12	.18	.39*	.02	.10	.14	.58**	.41*	.29	.09	.26	.28	-.29	.55**	.22
EFCH4	-.32	-.20	-.14	-.40	-.42**	-.48**	-.59**	-.26	-.19	-.17	-.21	-.43**	-.12	-.13	-.24	-.60**	-.49**	-.35	-.16	-.31	-.37*	.45**	-.55**	-.04
EFNMHC	-.15	-.13	-.12	-.38	-.31	-.39*	-.54**	-.31	-.25	-.17	-.21	-.47**	-.09	-.09	-.18	-.64**	-.45*	-.34	-.09	-.31	-.34	.49**	-.55**	.01
W_FLUX	-.57	-.24	-.22	-.30	-.17	-.20	-.06	-.07	-.18	-.13	-.13	-.06	-.20	-.00	-.14	-.10	-.16	-.07	-.17	-.11	-.17	.14	-.32	-.18
I_R	-.16	-.15	-.12	-.06	.27	.20	.44**	.17	-.01	.01	-.00	.24	-.19	-.06	-.06	.39*	.18	.17	-.10	.10	.09	-.11	.15	.03
C_PM	-.46	-.01	-.15	.08	.07	.21	.13	.00	.09	.08	.07	.03	-.11	-.05	-.02	.05	.04	-.08	.04	-.04	.03	-.19	.25	.02
C_PM2.5	-.44	-.06	-.14	.05	-.03	.17	.02	-.03	-.04	-.05	-.07	-.07	-.13	-.09	-.07	.00	.00	-.15	-.02	-.11	-.06	-.16	.07	-.11
CO_PPM	-.52	-.14	-.22	-.11	-.14	-.01	-.15	-.10	.14	.11	.04	-.07	-.13	-.10	-.08	-.21	-.10	-.22	-.12	-.24	-.11	-.11	.03	-.10
CO2_PPM	-.24	-.01	-.10	.17	.26	.33*	.37*	.14	.29	.29	.28	.23	-.04	-.03	-.00	.31	.21	-.04	-.05	-.00	.14	-.36	.50**	.09
CH4_PPM	-.52	-.20	-.25	-.24	-.17	-.03	-.20	-.17	-.04	-.06	-.08	-.17	-.19	-.14	-.17	-.34	-.21	-.28	-.17	-.29	-.23	.08	-.06	.03
NMHC_PPM	-.43	-.13	-.19	-.13	.00	.16	-.02	-.14	-.01	.04	.01	-.13	-.14	-.10	-.09	-.21	-.08	-.21	-.10	-.22	-.15	.05	.07	.12

2-tailed Signif: * - .01 ** - .001

F.3.4 All Fires -- Flaming and Smoldering (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	-.58**	.56**	-.35	-.29	.33	.38*	.16	-.29	.45**	.49**	.14	-.11	-.19	-.16	-.11	-.36	.08	.05
EC	-.58**	1.00	.35	.48**	.55**	-.39*	-.48**	-.48**	.55**	-.55**	-.55**	-.32	.15	.25	.07	.03	.50**	-.06	.07
TC	.56**	.35	1.00	.08	.22	-.00	-.07	-.30	.22	-.04	.01	-.18	.03	.02	-.11	-.10	.09	.03	.12
CARBON	-.35	.48**	.08	1.00	.53**	-.40*	-.45**	-.45**	.53**	-.52**	-.49**	-.24	.33	.78**	.63**	.67**	.00**	.55**	.72**
CMBSTEFF	-.29	.55**	.22	.53**	1.00	-.73**	-.83**	-.97**	.00**	-.75**	-.62**	-.03	.50**	.28	.09	-.02	.56**	-.05	.15
EFPM	.33	-.39*	-.00	-.40*	-.73**	1.00	.92**	.62**	-.73**	.61**	.51**	-.04	-.38*	-.02	.06	-.05	-.41*	.01	-.10
EFPM2.5	.38*	-.48**	-.07	-.45**	-.83**	.92**	1.00	.75**	-.83**	.74**	.60**	-.01	-.44**	-.05	.11	.05	-.47**	.11	-.07
EFCO	.16	-.48**	-.30	-.45**	-.97**	.62**	.75**	1.00	-.97**	.64**	.50**	-.04	-.52**	-.21	-.01	.13	-.47**	.10	-.11
EFCO2	-.29	.55**	.22	.53**	.00**	-.73**	-.83**	-.97**	1.00	-.75**	-.62**	-.03	.50**	.28	.09	-.02	.55**	-.05	.15
EFCH4	.45**	-.55**	-.04	-.52**	-.75**	.61**	.74**	.64**	-.75**	1.00	.89**	.38*	-.34	-.32	-.23	-.06	-.54**	.16	-.06
EFNMHC	.49**	-.55**	.01	-.49**	-.62**	.51**	.60**	.50**	-.62**	.89**	1.00	.36*	-.35*	-.28	-.21	-.07	-.50**	.19	.07
W_FLUX	.14	-.32	-.18	-.24	-.03	-.04	-.01	-.04	-.03	.38*	.36*	1.00	.52**	-.19	-.19	-.13	-.24	.10	-.03
I_R	-.11	.15	.03	.33	.50**	-.38*	-.44**	-.52**	.50**	-.34	-.35*	.52**	1.00	.13	.01	-.03	.34*	.02	.12
C_PM	-.19	.25	.02	.78**	.28	-.02	-.05	-.21	.28	-.32	-.28	-.19	.13	1.00	.91**	.80**	.75**	.66**	.77**
C_PM2.5	-.16	.07	-.11	.63**	.09	.06	.11	-.01	.09	-.23	-.21	-.19	.01	.91**	1.00	.84**	.60**	.69**	.72**
CO_PPM	-.11	.03	-.10	.67**	-.02	-.05	.05	.13	-.02	-.06	-.07	-.13	-.03	.80**	.84**	1.00	.63**	.88**	.79**
CO2_PPM	-.36	.50**	.09	.00**	.56**	-.41*	-.47**	-.47**	.55**	-.54**	-.50**	-.24	.34*	.75**	.60**	.63**	1.00	.52**	.69**
CH4_PPM	.08	-.06	.03	.55**	-.05	.01	.11	.10	-.05	.16	.19	.10	.02	.66**	.69**	.88**	.52**	1.00	.91**
NMHC_PPM	.05	.07	.12	.72**	.15	-.10	-.07	-.11	.15	-.06	.07	-.03	.12	.77**	.72**	.79**	.69**	.91**	1.00

2-tailed Signif: * - .01 ** - .001

P.4.1 All Fires -- Fire Average (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
NA	1.00	.37	.97	.	.24	-.31	-.73	-.38	.46	-.11	-.39	.41	.91	.23	.23	-.09	.98	.	.	.	.18	-.71	.14	-.95
AL	.37	1.00	.96**	.97**	.43	.79**	.67**	.82**	-.01	-.01	.08	.26	.90**	.13	.28	.52	.54	.16	.88**	.70*	.50	-.39	.05	-.35
SI	.97	.96**	1.00	.97**	.43	.86**	.78**	.89**	-.03	-.03	.05	.13	.90**	.13	.24	.58*	.44	.11	.94**	.76**	.45	-.30	-.01	-.28
P	.	.97**	.97**	1.00	.39	.91**	.85**	.89**	.93**	.60*	.85**	.25	.94**	.13	.52	.60*	.54	.17	.93**	.73**	.78**	.16	.72*	.48
S	.24	.43	.43	.39	1.00	.55*	.29	.25	-.22	-.20	-.26	-.31	.27	.01	-.15	.12	.26	.14	.32	.37	.05	.13	-.20	.08
CL	-.31	.79**	.86**	.91**	.55*	1.00	.85**	.74**	-.17	-.12	-.10	-.14	.62**	.06	.15	.56*	.48	.14	.88**	.71**	.29	-.10	-.07	-.11
K	-.73	.67**	.78**	.85**	.29	.85**	1.00	.83**	-.18	-.10	-.14	-.08	.53*	.13	.08	.81**	.30	.12	.94**	.73**	.32	.04	.30	.11
CA	-.38	.82**	.89**	.89**	.25	.74**	.83**	1.00	.11	.10	.18	.20	.76**	.18	.33	.72**	.27	.16	.95**	.84**	.47	-.17	.24	-.10
TI	.46	-.01	-.03	.93**	-.22	-.17	-.18	.11	1.00	.76**	.90**	.60*	.16	.05	.73**	-.11	.14	.15	.87**	.60*	.71**	-.54	.47	-.21
V	-.11	-.01	-.03	.60*	-.20	-.12	-.10	.10	.76**	1.00	.67**	.34	.08	.04	.57*	-.03	.06	.02	.68*	.32	.61*	-.32	.41	-.05
CR	-.39	.08	.05	.85**	-.26	-.10	-.14	.18	.90**	.67**	1.00	.63*	.24	.00	.69**	-.15	.08	.08	.69*	.46	.65**	-.39	.40	-.12
MN	.41	.26	.13	.25	-.31	-.14	-.08	.20	.60*	.34	.63*	1.00	.41	.01	.68**	.11	.41	.45	.11	.13	.64*	-.09	.37	.01
FE	.91	.90**	.90**	.94**	.27	.62**	.53*	.76**	.16	.08	.24	.41	1.00	.09	.33	.47	.53	.09	.88**	.65*	.58*	-.18	.06	-.16
NI	.23	.13	.13	.13	.01	.06	.13	.18	.05	.04	.00	.01	.09	1.00	.02	.34	.26	-.05	.04	.18	.30	-.42	.64*	-.01
CU	.23	.28	.24	.52	-.15	.15	.08	.33	.73**	.57*	.69**	.68**	.33	.02	1.00	.16	.38	.55	.42	.66*	.70**	-.52	.35	-.26
ZN	-.09	.52	.58*	.60*	.12	.56*	.81**	.72**	-.11	-.03	-.15	.11	.47	.34	.16	1.00	.37	.44	.67*	.75**	.41	-.04	.41	.20
BR	.98	.54	.44	.54	.26	.48	.30	.27	.14	.06	.08	.41	.53	.26	.38	.37	1.00	.54	.33	.43	.54*	-.36	.18	-.22
AG	.	.16	.11	.17	.14	.14	.12	.16	.15	.02	.08	.45	.09	-.05	.55	.44	.54	1.00	.16	.59	.27	-.24	-.04	-.20
CD	.	.88**	.94**	.93**	.32	.88**	.94**	.95**	.87**	.68*	.69*	.11	.88**	.04	.42	.67*	.33	.16	1.00	.77**	.64*	.27	.63	.52
SN	.	.70*	.76**	.73**	.37	.71**	.73**	.84**	.60*	.32	.46	.13	.65*	.18	.66*	.75**	.43	.59	.77**	1.00	.54	-.23	-.07	-.21
PB	.18	.50	.45	.78**	.05	.29	.32	.47	.71**	.61*	.65**	.64*	.58*	.30	.70**	.41	.54*	.27	.64*	.54	1.00	-.48	.61*	-.09
OC	-.71	-.39	-.30	.16	.13	-.10	.04	-.17	-.54	-.32	-.39	-.09	-.18	-.42	-.52	-.04	-.36	-.24	.27	-.23	-.48	1.00	.16	.97**
EC	.14	.05	-.01	.72*	-.20	-.07	.30	.24	.47	.41	.40	.37	.06	.64*	.35	.41	.18	-.04	.63	-.07	.61*	.16	1.00	.39
TC	-.95	-.35	-.28	.48	.08	-.11	.11	-.10	-.21	-.05	-.12	.01	-.16	-.01	-.26	.20	-.22	-.20	.52	-.21	-.09	.97**	.39	1.00

2-tailed Signif: * - .01 ** - .001

F.4.2 All Fires -- Fire Average (p.2 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.71	.14	-.95	-.92	-.46	.63	.52	.40	-.46	.76	.46	-.99	.	-.94	-.99	-.96	-.91	-.95	-.69
AL	-.39	.05	-.35	-.03	-.06	-.17	.00	.09	-.06	-.24	-.18	-.27	.	-.12	-.04	-.04	-.03	-.12	-.10
SI	-.30	-.01	-.28	-.09	-.00	-.14	.01	.00	-.00	-.16	-.13	-.21	.	-.16	-.09	-.12	-.08	-.14	-.13
P	.16	.72*	.48	.07	-.04	-.20	-.18	.13	-.04	-.24	-.21	-.33	.	-.06	-.03	.09	.06	.00	-.03
S	.13	-.20	.08	.17	.21	-.07	-.19	-.23	.21	-.14	.12	-.20	.	.12	.07	-.06	.19	.12	.26
CL	-.10	-.07	-.11	-.09	.06	.02	-.03	-.13	.06	-.14	-.05	-.20	.	-.07	-.09	-.17	-.08	-.10	-.07
K	.04	.30	.11	-.16	.33	-.17	-.20	-.38	.33	-.15	-.14	.00	.	-.24	-.25	-.30	-.14	-.23	-.23
CA	-.17	.24	-.10	-.04	.17	-.33	-.17	-.09	.17	-.16	-.20	-.08	.	-.20	-.11	-.05	-.04	-.10	-.13
TI	-.54	.47	-.21	.23	-.28	-.13	-.06	.56*	-.28	-.03	-.21	-.24	.	.14	.13	.43	.22	.20	.09
V	-.32	.41	-.05	.37	-.20	-.08	-.11	.41	-.20	-.09	-.09	-.21	.	.27	.18	.53	.36	.31	.35
CR	-.39	.40	-.12	.31	-.40	-.12	-.03	.67**	-.40	-.04	-.21	-.24	.	.24	.27	.59*	.28	.32	.17
MN	-.09	.37	.01	-.04	-.06	-.32	-.16	.21	-.06	-.10	-.27	.05	.	-.20	-.11	.11	-.05	-.08	-.20
FE	-.18	.06	-.16	-.05	-.13	-.15	.12	.19	-.13	-.15	-.16	-.23	.	-.13	-.01	-.03	-.05	-.13	-.15
NI	-.42	.64*	-.01	.12	.10	-.39	-.38	-.04	.10	.08	-.07	.13	.	-.14	-.12	.05	.13	.23	.11
CU	-.52	.35	-.26	-.07	-.07	-.13	-.22	.25	-.07	-.15	-.18	-.04	.	-.12	-.17	.13	-.08	-.09	-.11
ZN	-.04	.41	.20	-.12	.62*	-.43	-.51	-.57*	.62*	-.43	-.50	.00	.	-.30	-.32	-.30	-.09	-.27	-.32
BR	-.36	.18	-.22	-.12	.01	-.11	-.26	.04	.01	-.31	-.22	-.29	.	-.19	-.24	-.14	-.11	-.19	-.17
AG	-.24	-.04	-.20	-.04	.47	-.23	-.44	-.40	.47	-.54	-.54	-.05	.	-.15	-.16	-.09	-.03	-.19	-.18
CD	.27	.63	.52	.02	.03	-.14	-.05	.00	.03	-.17	-.23	-.22	.	-.08	-.03	-.01	.02	-.06	-.10
SN	-.23	-.07	-.21	-.10	.37	-.28	-.36	-.31	.37	-.34	-.33	-.07	.	-.23	-.21	-.18	-.09	-.18	-.18
PB	-.48	.61*	-.09	.25	.03	-.31	-.39	.20	.03	-.33	-.43	-.25	.	.07	.01	.27	.25	.11	.01
OC	1.00	.16	.97**	.09	.28	.13	-.19	-.46	.28	.12	.36	.09	.	.12	-.01	-.11	.10	.17	.26
EC	.16	1.00	.39	.21	.23	-.25	-.31	-.09	.23	-.47	-.45	-.47	.	.09	.02	.11	.22	.00	-.02
TC	.97**	.39	1.00	.13	.32	.07	-.26	-.45	.32	-.00	.23	-.02	.	.13	-.00	-.07	.15	.16	.23

2-tailed Signif: * - .01 ** - .001

F.4.3 All Fires -- Fire Average (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.71	-.39	-.30	.16	.13	-.10	.04	-.17	-.54	-.32	-.39	-.09	-.18	-.42	-.52	-.04	-.36	-.24	.27	-.23	-.48	1.00	.16	.97**
EC	.14	.05	-.01	.72*	-.20	-.07	.30	.24	.47	.41	.40	.37	.06	.64*	.35	.41	.18	-.04	.63	-.07	.61*	.16	1.00	.39
TC	-.95	-.35	-.28	.48	.08	-.11	.11	-.10	-.21	-.05	-.12	.01	-.16	-.01	-.26	.20	-.22	-.20	.52	-.21	-.09	.97**	.39	1.00
CARBON	-.92	-.03	-.09	.07	.17	-.09	-.16	-.04	.23	.37	.31	-.04	-.05	.12	-.07	-.12	-.12	-.04	.02	-.10	.25	.09	.21	.13
CMBSTEFF	-.46	-.06	-.00	-.04	.21	.06	.33	.17	-.28	-.20	-.40	-.06	-.13	.10	-.07	.62*	.01	.47	.03	.37	.03	.28	.23	.32
EFPM	.63	-.17	-.14	-.20	-.07	.02	-.17	-.33	-.13	-.08	-.12	-.32	-.15	-.39	-.13	-.43	-.11	-.23	-.14	-.28	-.31	.13	-.25	.07
EFPM2.5	.52	.00	.01	-.18	-.19	-.03	-.20	-.17	-.06	-.11	-.03	-.16	.12	-.38	-.22	-.51	-.26	-.44	-.05	-.36	-.39	-.19	-.31	-.26
EFCO	.40	.09	.00	.13	-.23	-.13	-.38	-.09	.56*	.41	.67**	.21	.19	-.04	.25	-.57*	.04	-.40	.00	-.31	.20	-.46	-.09	-.45
EFCO2	-.46	-.06	-.00	-.04	.21	.06	.33	.17	-.28	-.20	-.40	-.06	-.13	.10	-.07	.62*	.01	.47	.03	.37	.03	.28	.23	.32
EFCH4	.76	-.24	-.16	-.24	-.14	-.14	-.15	-.16	-.03	-.09	-.04	-.10	-.15	.08	-.15	-.43	-.31	-.54	-.17	-.34	-.33	.12	-.47	-.00
EFNMHC	.46	-.18	-.13	-.21	.12	-.05	-.14	-.20	-.21	-.09	-.21	-.27	-.16	-.07	-.18	-.50	-.22	-.54	-.23	-.33	-.43	.36	-.45	.23
W_FLUX	-.99	-.27	-.21	-.33	-.20	-.20	.00	-.08	-.24	-.21	-.24	.05	-.23	.13	-.04	.00	-.29	-.05	-.22	-.07	-.25	.09	-.47	-.02
I_R	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
C_PM	-.94	-.12	-.16	-.06	.12	-.07	-.24	-.20	.14	.27	.24	-.20	-.13	-.14	-.12	-.30	-.19	-.15	-.08	-.23	.07	.12	.09	.13
C_PM2.5	-.99	-.04	-.09	-.03	.07	-.09	-.25	-.11	.13	.18	.27	-.11	-.01	-.12	-.17	-.32	-.24	-.16	-.03	-.21	.01	-.01	.02	-.00
CO_PPM	-.96	-.04	-.12	.09	-.06	-.17	-.30	-.05	.43	.53	.59*	.11	-.03	.05	.13	-.30	-.14	-.09	-.01	-.18	.27	-.11	.11	-.07
CO2_PPM	-.91	-.03	-.08	.06	.19	-.08	-.14	-.04	.22	.36	.28	-.05	-.05	.13	-.08	-.09	-.11	-.03	.02	-.09	.25	.10	.22	.15
CH4_PPM	-.95	-.12	-.14	.00	.12	-.10	-.23	-.10	.20	.31	.32	-.08	-.13	.23	-.09	-.27	-.19	-.19	-.06	-.18	.11	.17	.00	.16
NMHC_PPM	-.69	-.10	-.13	-.03	.26	-.07	-.23	-.13	.09	.35	.17	-.20	-.15	.11	-.11	-.32	-.17	-.18	-.10	-.18	.01	.26	-.02	.23

2-tailed Signif: * - .01 ** - .001

F.4.4 All Fires -- Fire Average (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	BFPM	BFPM2.5	BFCO	BFCO2	BFCH4	BFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	.16	.97**	.09	.28	.13	-.19	-.46	.28	.12	.36	.09	.	.12	-.01	-.11	.10	.17	.26
EC	.16	1.00	.39	.21	.23	-.25	-.31	-.09	.23	-.47	-.45	-.47	.	.09	.02	.11	.22	.00	-.02
TC	.97**	.39	1.00	.13	.32	.07	-.26	-.45	.32	-.00	.23	-.02	.	.13	-.00	-.07	.15	.16	.23
CARBON	.09	.21	.13	1.00	.34	-.40	-.41	-.10	.34	-.50*	-.37	-.28	.	.73**	.79**	.79**	.00**	.71**	.72**
CMBSTEFF	.28	.23	.32	.34	1.00	-.56*	-.75**	-.91**	1.00**	-.52*	-.41	.24	.	-.05	-.06	-.13	.38	-.08	-.02
BFPM	.13	-.25	.07	-.40	-.56*	1.00	.80**	.32	-.56*	.26	.28	-.10	.	.12	-.06	-.22	-.41	-.27	-.22
BFPM2.5	-.19	-.31	-.26	-.41	-.75**	.80**	1.00	.59**	-.75**	.37	.22	-.11	.	-.02	.03	-.17	-.43	-.26	-.29
BFCO	-.46	-.09	-.45	-.10	-.91**	.32	.59**	1.00	-.91**	.29	.15	-.36	.	.18	.24	.39	-.14	.21	.11
BFCO2	.28	.23	.32	.34	1.00**	-.56*	-.75**	-.91**	1.00	-.52*	-.41	.24	.	-.05	-.06	-.13	.38	-.08	-.02
BFCH4	.12	-.47	-.00	-.50*	-.52*	.26	.37	.29	-.52*	1.00	.81**	.57*	.	-.39	-.40	-.32	-.50*	-.03	-.10
BFNMHC	.36	-.45	.23	-.37	-.41	.28	.22	.15	-.41	.81**	1.00	.40	.	-.23	-.31	-.25	-.38	.02	.15
W_FLUX	.09	-.47	-.02	-.28	.24	-.10	-.11	-.36	.24	.57*	.40	1.00	.	-.33	-.33	-.30	-.27	-.12	-.16
I_R	.	.	.	.	.	.	.	.	.	.	.	.	1.00	.	.	.	.	.	.
C_PM	.12	.09	.13	.73**	-.05	.12	-.02	.18	-.05	-.39	-.23	-.33	.	1.00	.94**	.82**	.70**	.76**	.77**
C_PM2.5	-.01	.02	-.00	.79**	-.06	-.06	.03	.24	-.06	-.40	-.31	-.33	.	.94**	1.00	.88**	.76**	.77**	.75**
CO_PPM	-.11	.11	-.07	.79**	-.13	-.22	-.17	.39	-.13	-.32	-.25	-.30	.	.82**	.88**	1.00	.75**	.85**	.80**
CO2_PPM	.10	.22	.15	.00**	.38	-.41	-.43	-.14	.38	-.50*	-.38	-.27	.	.70**	.76**	.75**	1.00	.67**	.68**
CH4_PPM	.17	.00	.16	.71**	-.08	-.27	-.26	.21	-.08	-.03	.02	-.12	.	.76**	.77**	.85**	.67**	1.00	.92**
NMHC_PPM	.26	-.02	.23	.72**	-.02	-.22	-.29	.11	-.02	-.10	.15	-.16	.	.77**	.75**	.80**	.68**	.92**	1.00

2-tailed Signif: * - .01 ** - .001

P.5.1 Broadcast Burns -- Flaming (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
NA	1.00	-.05	-.05	.	-.45	-.57	-.57	-.15	-.06	-.11	-.11	.25	-.10	.22	.22	-.18	-.34	.	.	.	-.11	-.12	-.14	-.68
AL	-.05	1.00	.90**	.74*	.36	.11	.28	.02	.10	.10	.26	.51	.89**	.98**	.97**	.09	.88**	.98**	.98**	.97**	.93**	-.20	.22	-.01
SI	-.05	.90**	1.00	.93**	.45	.20	.33	.26	-.04	-.03	.13	.35	.79**	.88**	.89**	.38	.92**	.84**	.84**	.90**	.91**	.31	-.11	.23
P	.	.74*	.93**	1.00	.43	.10	.37	.58	.82**	.47	.71*	.75*	.75*	.71*	.76*	.67*	.82**	.64	.65	.73*	.88**	-.04	.88**	.87**
S	-.45	.36	.45	.43	1.00	.75**	.92**	.01	-.19	-.05	-.02	.09	.24	.26	.30	.51	.59	.30	.26	.24	.24	.44	.06	.53
CL	-.57	.11	.20	.10	.75**	1.00	.75**	-.18	-.25	-.15	-.16	-.14	-.03	-.00	.12	.21	.46	-.02	-.08	-.05	-.04	.39	-.11	.33
K	-.57	.28	.33	.37	.92**	.75**	1.00	.05	-.07	.05	.07	.21	.19	.14	.21	.67*	.52	.19	.13	.09	.17	.26	.34	.60*
CA	-.15	.02	.26	.58	.01	-.18	.05	1.00	.08	.08	.07	.28	.00	-.08	-.02	.87**	.13	-.21	-.18	-.05	.20	-.19	.11	-.11
TI	-.06	.10	-.04	.82**	-.19	-.25	-.07	.08	1.00	.96**	.96**	.71**	.49	.15	.19	.19	.05	.92**	.93**	.93**	.29	-.73*	.50	-.38
V	-.11	.10	-.03	.47	-.05	-.15	.05	.08	.96**	1.00	.98**	.58*	.49	.12	.16	.24	.05	.85**	.84**	.81**	.25	-.52	.39	-.23
CR	-.11	.26	.13	.71*	-.02	-.16	.07	.07	.96**	.98**	1.00	.67*	.64*	.29	.33	.24	.20	.99**	.98**	.98**	.41	-.55	.43	-.24
MN	.25	.51	.35	.75*	.09	-.14	.21	.28	.71**	.58*	.67*	1.00	.62*	.53	.55	.28	.43	.80**	.79**	.76*	.63*	-.77**	.66*	-.23
FE	-.10	.89**	.79**	.75*	.24	-.03	.19	.00	.49	.49	.64*	.62*	1.00	.92**	.92**	.18	.77**	.97**	.98**	.98**	.93**	-.52	.43	-.17
NI	.22	.98**	.88**	.71*	.26	-.00	.14	-.08	.15	.12	.29	.53	.92**	1.00	.98**	.04	.84**	.97**	.98**	.97**	.95**	-.65*	.35	-.43
CU	.22	.97**	.89**	.76*	.30	.12	.21	-.02	.19	.16	.33	.55	.92**	.98**	1.00	.11	.89**	.95**	.95**	.96**	.94**	-.54	.40	-.25
ZN	-.18	.09	.38	.67*	.51	.21	.67*	.87**	.19	.24	.24	.28	.18	.04	.11	1.00	.32	-.06	-.05	.05	.30	-.13	.65*	.49
BR	-.34	.88**	.92**	.82**	.59	.46	.52	.13	.05	.05	.20	.43	.77**	.84**	.89**	.32	1.00	.80**	.78**	.83**	.85**	-.08	.12	.03
AG	.	.98**	.84**	.64	.30	-.02	.19	-.21	.92**	.85**	.99**	.80**	.97**	.97**	.95**	-.06	.80**	1.00	.99**	.97**	.90**	-.34	.61	.51
CD	.	.98**	.84**	.65	.26	-.08	.13	-.18	.93**	.84**	.98**	.79**	.98**	.98**	.95**	-.05	.78**	.99**	1.00	.96**	.92**	.06	.65	.67
SN	.	.97**	.90**	.73*	.24	-.05	.09	-.05	.93**	.81**	.98**	.76*	.98**	.97**	.96**	.05	.83**	.97**	.96**	1.00	.93**	-.11	.21	.17
PB	-.11	.93**	.91**	.88**	.24	-.04	.17	.20	.29	.25	.41	.63*	.93**	.95**	.94**	.30	.85**	.90**	.92**	.93**	1.00	-.69*	.50	-.34
OC	-.12	-.20	.31	-.04	.44	.39	.26	-.19	-.73*	-.52	-.55	-.77**	-.52	-.65*	-.54	-.13	-.08	-.34	.06	-.11	-.69*	1.00	-.52	.60*
EC	-.14	.22	-.11	.88**	.06	-.11	.34	.11	.50	.39	.43	.66*	.43	.35	.40	.65*	.12	.61	.65	.21	.50	-.52	1.00	.36
TC	-.68	-.01	.23	.87**	.53	.33	.60*	-.11	-.38	-.23	-.24	-.23	-.17	-.43	-.25	.49	.03	.51	.67	.17	-.34	.60*	.36	1.00

2-tailed Signif: * - .01 ** - .001

F.5.2 Broadcast Burns -- Flaming (p.2 of 4)

	OC	BC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.12	-.14	-.68	-.80	-.31	.46	.60	.29	-.31	.44	.68	-.81	-.79	-.79	-.62	-.68	-.81	-.66	-.65
AL	-.20	.22	-.01	-.27	-.05	.29	.08	-.12	-.06	-.11	.23	-.27	-.28	-.18	-.22	-.27	-.26	-.26	-.21
SI	.31	-.11	.23	-.31	-.01	.16	.01	-.21	-.01	-.19	.16	-.20	-.19	-.31	-.29	-.34	-.31	-.30	-.24
P	-.04	.88**	.87**	-.38	.16	.05	-.04	-.27	.16	-.34	-.10	-.26	-.21	-.52	-.40	-.40	-.37	-.37	-.37
S	.44	.06	.53	-.07	.23	-.22	-.29	-.54*	.24	-.36	-.05	.17	.22	-.21	-.18	-.33	-.06	-.19	-.08
CL	.39	-.11	.33	-.13	-.06	-.07	-.00	-.16	-.05	.02	.12	.06	-.01	-.19	-.05	-.19	-.13	-.04	.02
K	.26	.34	.60*	-.08	.33	-.29	-.34	-.58*	.34	-.44	-.26	.11	.16	-.28	-.25	-.36	-.07	-.25	-.19
CA	-.19	.11	-.11	.14	.35	-.29	-.25	-.23	.34	-.37	-.39	.20	.13	.09	.03	-.00	.15	-.06	-.06
TI	-.73*	.50	-.38	.22	.54	-.31	-.40	-.11	.53	-.28	-.25	-.08	.01	-.08	-.23	.04	.24	-.09	-.07
V	-.52	.39	-.23	.21	.49	-.27	-.36	-.22	.49	-.34	-.24	-.03	.01	-.09	-.24	-.01	.23	-.13	-.06
CR	-.55	.43	-.24	.15	.47	-.21	-.34	-.22	.46	-.35	-.19	-.09	-.05	-.14	-.29	-.05	.18	-.16	-.09
MN	-.77**	.66*	-.23	.02	.56*	-.27	-.41	-.35	.55*	-.40	-.32	-.17	-.07	-.19	-.33	-.21	.04	-.24	-.26
PB	-.52	.43	-.17	-.18	.11	.13	-.05	-.17	.10	-.21	.13	-.28	-.23	-.28	-.32	-.26	-.16	-.27	-.20
NI	-.65*	.35	-.43	-.28	-.21	.47	.27	.02	-.21	-.03	.31	-.33	-.27	-.22	-.23	-.22	-.28	-.23	-.19
CU	-.54	.40	-.25	-.29	-.18	.40	.24	.01	-.18	-.02	.32	-.37	-.33	-.29	-.27	-.23	-.29	-.24	-.20
ZN	-.13	.65*	.49	-.12	.55	-.48	-.44	-.69*	.56	-.71**	-.62*	.12	.10	-.34	-.29	-.34	-.10	-.40	-.39
BR	-.08	.12	.03	-.24	-.11	.22	.12	-.14	-.11	-.16	.16	-.26	-.26	-.32	-.23	-.23	-.24	-.24	-.20
AG	-.34	.61	.51	-.41	-.27	.55	.28	.08	-.27	.02	.34	-.40	-.34	-.23	-.31	-.30	-.42	-.26	-.23
CD	.06	.65	.67	-.40	-.29	.57	.34	.10	-.29	.03	.36	-.36	-.29	-.20	-.24	-.27	-.40	-.24	-.21
SN	-.11	.21	.17	-.40	-.23	.52	.25	.05	-.23	.03	.36	-.42	-.36	-.24	-.33	-.29	-.40	-.24	-.21
PB	-.69*	.50	-.34	-.22	-.02	.30	.10	-.10	-.02	-.19	.12	-.25	-.17	-.25	-.28	-.23	-.22	-.27	-.24
OC	1.00	-.52	.60*	-.15	-.35	.27	.21	-.12	-.35	.07	.27	.26	.12	.01	.06	-.13	-.17	.03	.14
BC	-.52	1.00	.36	-.08	.71*	-.57	-.62	-.57	.72**	-.50	-.54	.03	.06	-.44	-.61	-.34	-.06	-.31	-.33
TC	.60*	.36	1.00	-.24	.26	-.22	-.31	-.65*	.26	-.38	-.19	.32	.18	-.38	-.45	-.45	-.24	-.24	-.14

2-tailed Signif: * - .01 ** - .001

F.5.3 Broadcast Burns -- Flaming (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.12	-.20	.31	-.04	.44	.39	.26	-.19	-.73*	-.52	-.55	-.77**	-.52	-.65*	-.54	-.13	-.08	-.34	.06	-.11	-.69*	1.00	-.52	.60*
EC	-.14	.22	-.11	.88**	.06	-.11	.34	.11	.50	.39	.43	.66*	.43	.35	.40	.65*	.12	.61	.65	.21	.50	-.52	1.00	.36
TC	-.68	-.01	.23	.87**	.53	.33	.60*	-.11	-.38	-.23	-.24	-.23	-.17	-.43	-.25	.49	.03	.51	.67	.17	-.34	.60*	.36	1.00
CARBON	-.80	-.27	-.31	-.38	-.07	-.13	-.08	.14	.22	.21	.15	.02	-.18	-.28	-.29	-.12	-.24	-.41	-.40	-.40	-.22	-.15	-.08	-.24
CMBSTEFF	-.31	-.05	-.01	.16	.23	-.06	.33	.35	.54	.49	.47	.56*	.11	-.21	-.18	.55	-.11	-.27	-.29	-.23	-.02	-.35	.71*	.26
EFPM	.46	.29	.16	.05	-.22	-.07	-.29	-.29	-.31	-.27	-.21	-.27	.13	.47	.40	-.48	.22	.55	.57	.52	.30	.27	-.57	-.22
EFPM2.5	.60	.08	.01	-.04	-.29	-.00	-.34	-.25	-.40	-.36	-.34	-.41	-.05	.27	.24	-.44	.12	.28	.34	.25	.10	.21	-.62	-.31
EFCO	.29	-.12	-.21	-.27	-.54*	-.16	-.58*	-.23	-.11	-.22	-.22	-.35	-.17	.02	.01	-.69*	-.14	.08	.10	.05	-.10	-.12	-.57	-.65*
EFCO2	-.31	-.06	-.01	.16	.24	-.05	.34	.34	.53	.49	.46	.55*	.10	-.21	-.18	.56	-.11	-.27	-.29	-.23	-.02	-.35	.72**	.26
EFCH4	.44	-.11	-.19	-.34	-.36	.02	-.44	-.37	-.28	-.34	-.35	-.40	-.21	-.03	-.02	-.71**	-.16	.02	.03	.03	-.19	.07	-.50	-.38
EFNMHC	.68	.23	.16	-.10	-.05	.12	-.26	-.39	-.25	-.24	-.19	-.32	.13	.31	.32	-.62*	.16	.34	.36	.36	.12	.27	-.54	-.19
W_FLUX	-.81	-.27	-.20	-.26	.17	.06	.11	.20	-.08	-.03	-.09	-.17	-.28	-.33	-.37	.12	-.26	-.40	-.36	-.42	-.25	.26	.03	.32
I_R	-.79	-.28	-.19	-.21	.22	-.01	.16	.13	.01	.01	-.05	-.07	-.23	-.27	-.33	.10	-.26	-.34	-.29	-.36	-.17	.12	.06	.18
C_PM	-.79	-.18	-.31	-.52	-.21	-.19	-.28	.09	-.08	-.09	-.14	-.19	-.28	-.22	-.29	-.34	-.32	-.23	-.20	-.24	-.25	.01	-.44	-.38
C_PM2.5	-.62	-.22	-.29	-.40	-.18	-.05	-.25	.03	-.23	-.24	-.29	-.33	-.32	-.23	-.27	-.29	-.23	-.31	-.24	-.33	-.28	.06	-.61	-.45
CO_PPM	-.68	-.27	-.34	-.40	-.33	-.19	-.36	-.00	.04	-.01	-.05	-.21	-.26	-.22	-.23	-.34	-.23	-.30	-.27	-.29	-.23	-.13	-.34	-.45
CO2_PPM	-.81	-.26	-.31	-.37	-.06	-.13	-.07	.15	.24	.23	.18	.04	-.16	-.28	-.29	-.10	-.24	-.42	-.40	-.40	-.22	-.17	-.06	-.24
CH4_PPM	-.66	-.26	-.30	-.37	-.19	-.04	-.25	-.06	-.09	-.13	-.16	-.24	-.27	-.23	-.24	-.40	-.24	-.26	-.24	-.24	-.27	.03	-.31	-.24
NMHC_PPM	-.65	-.21	-.24	-.37	-.08	.02	-.19	-.06	-.07	-.06	-.09	-.26	-.20	-.19	-.20	-.39	-.20	-.23	-.21	-.21	-.24	.14	-.33	-.14

2-tailed Signif: * - .01 ** - .001

F.5.4 Broadcast Burns -- Flaming (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	-.52	.60*	-.15	-.35	.27	.21	-.12	-.35	.07	.27	.26	.12	.01	.06	-.13	-.17	.03	.14
EC	-.52	1.00	.36	-.08	.71*	-.57	-.62	-.57	.72**	-.50	-.54	.03	.06	-.44	-.61	-.34	-.06	-.31	-.33
TC	.60*	.36	1.00	-.24	.26	-.22	-.31	-.65*	.26	-.38	-.19	.32	.18	-.38	-.45	-.45	-.24	-.24	-.14
CARBON	-.15	-.08	-.24	1.00	.26	-.46	-.41	.02	.26	-.06	-.21	.67**	.60*	.62*	.47	.84**	.00**	.82**	.79**
CMBSTEFF	-.35	.71*	.26	.26	1.00	-.83**	-.93**	-.84**	.00**	-.70**	-.60*	.12	.25	-.32	-.51	-.23	.29	-.11	-.07
EFPM	.27	-.57	-.22	-.46	-.83**	1.00	.90**	.67**	-.83**	.66*	.63*	-.19	-.32	.32	.39	-.02	-.48	-.05	-.09
EFPM2.5	.21	-.62	-.31	-.41	-.93**	.90**	1.00	.82**	-.92**	.69**	.55	-.24	-.32	.31	.56*	.12	-.44	.02	-.07
EFCO	-.12	-.57	-.65*	.02	-.84**	.67**	.82**	1.00	-.85**	.64**	.38	-.00	-.17	.52	.69**	.53*	-.01	.28	.18
EFCO2	-.35	.72**	.26	.26	.00**	-.83**	-.92**	-.85**	1.00	-.68**	-.58*	.11	.25	-.32	-.51	-.24	.29	-.11	-.07
EFCH4	.07	-.50	-.38	-.06	-.70**	.66*	.69**	.64**	-.68**	1.00	.85**	-.15	-.12	.27	.39	.29	-.08	.46	.43
EFNMHC	.27	-.54	-.19	-.21	-.60*	.63*	.55	.38	-.58*	.85**	1.00	-.22	-.21	.05	.13	.04	-.22	.28	.36
W_FLUX	.26	.03	.32	.67**	.12	-.19	-.24	-.00	.11	-.15	-.22	1.00	.84**	.57*	.35	.59*	.66**	.54*	.55*
I_R	.12	.06	.18	.60*	.25	-.32	-.32	-.17	.25	-.12	-.21	.84**	1.00	.42	.26	.38	.60*	.47	.46
C_PM	.01	-.44	-.38	.62*	-.32	.32	.31	.52	-.32	.27	.05	.57*	.42	1.00	.86**	.81**	.60*	.76**	.73**
C_PM2.5	.06	-.61	-.45	.47	-.51	.39	.56*	.69**	-.51	.39	.13	.35	.26	.86**	1.00	.82**	.44	.70**	.61*
CO_PPM	-.13	-.34	-.45	.84**	-.23	-.02	.12	.53*	-.24	.29	.04	.59*	.38	.81**	.82**	1.00	.82**	.88**	.80**
CO2_PPM	-.17	-.06	-.24	.00**	.29	-.48	-.44	-.01	.29	-.08	-.22	.66**	.60*	.60*	.44	.82**	1.00	.80**	.77**
CH4_PPM	.03	-.31	-.24	.82**	-.11	-.05	.02	.28	-.11	.46	.28	.54*	.47	.76**	.70**	.88**	.80**	1.00	.97**
NMHC_PPM	.14	-.33	-.14	.79**	-.07	-.09	-.07	.18	-.07	.43	.36	.55*	.46	.73**	.61*	.80**	.77**	.97**	1.00

2-tailed Signif: * - .01 ** - .001

F.6.1 Broadcast Burns -- Smoldering (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
NA	1.00	.98*	.90	.	.69	.79	-.37	.53	.99**	-.11	.97*	.97*	.27	.85	.85	.77	.31	.	.	.	.95	-.76	.72	-.69
AL	.98*	1.00	.95**	.94**	.14	.36	.65**	.86**	-.00	-.01	.04	.31	.85**	.40	-.02	.62*	.07	.35	.87**	.86**	.15	-.30	.25	-.27
SI	.90	.95**	1.00	.95**	.08	.32	.70**	.91**	-.11	-.09	-.05	.13	.88**	.33	-.10	.64*	-.08	.16	.90**	.87**	-.04	-.41	.11	-.40
P	.	.94**	.95**	1.00	.07	.46	.90**	.91**	.60	.36	.94**	.26	.86**	.89**	.70*	.70*	.18	.12	.85**	.80**	.18	-.27	.22	-.21
S	.69	.14	.08	.07	1.00	.61*	.09	-.05	-.20	-.23	-.21	-.20	-.00	-.22	-.22	-.20	.14	-.05	-.09	.01	-.22	.08	-.27	.04
CL	.79	.36	.32	.46	.61*	1.00	.58*	.14	-.32	-.35	-.27	-.02	.18	-.21	-.30	.12	.32	-.16	.04	.04	-.21	.05	-.16	.03
K	-.37	.65**	.70**	.90**	.09	.58*	1.00	.69**	-.29	-.25	-.19	-.08	.48	.15	-.23	.78**	-.10	-.03	.75*	.68*	-.20	.16	.28	.19
CA	.53	.86**	.91**	.91**	-.05	.14	.69**	1.00	.10	.10	.18	.20	.80**	.56	.15	.73**	-.17	.12	.96**	.90**	.09	-.43	.28	-.40
TI	.99**	-.00	-.11	.60	-.20	-.32	-.29	.10	1.00	.69*	.98**	.79**	.02	.85**	.96**	.15	.46	.81**	.64	.71*	.84**	-.59	.46	-.51
V	-.11	-.01	-.09	.36	-.23	-.35	-.25	.10	.69*	1.00	.63*	.51	-.02	.68*	.73**	.14	.24	.87**	.55	.62	.66*	-.23	.34	-.15
CR	.97*	.04	-.05	.94**	-.21	-.27	-.19	.18	.98**	.63*	1.00	.79**	.07	.88**	.97**	.23	.45	.12	.78**	.69*	.77**	-.58	.40	-.52
MN	.97*	.31	.13	.26	-.20	-.02	-.08	.20	.79**	.51	.79**	1.00	.38	.65*	.76**	.14	.66*	.49	-.01	-.01	.85**	-.28	.46	-.22
FE	.27	.85**	.88**	.86**	-.00	.18	.48	.80**	.02	-.02	.07	.38	1.00	.36	-.00	.58	.03	.11	.74*	.73*	.01	-.46	.11	-.46
NI	.85	.40	.33	.89**	-.22	-.21	.15	.56	.85**	.68*	.88**	.65*	.36	1.00	.88**	.56	.21	.29	.95**	.95**	.74**	-.53	.51	-.44
CU	.85	-.02	-.10	.70*	-.22	-.30	-.23	.15	.96**	.73**	.97**	.76**	-.00	.88**	1.00	.22	.32	-.11	.51	.48	.77**	-.48	.41	-.41
ZN	.77	.62*	.64*	.70*	-.20	.12	.78**	.73**	.15	.14	.23	.14	.58	.56	.22	1.00	-.16	.05	.71*	.70*	.17	-.28	.67*	-.11
BR	.31	.07	-.08	.18	.14	.32	-.10	-.17	.46	.24	.45	.66*	.03	.21	.32	-.16	1.00	.36	-.16	-.12	.53	-.64	.32	-.61
AG	.	.35	.16	.12	-.05	-.16	-.03	.12	.81**	.87**	.12	.49	.11	.29	-.11	.05	.36	1.00	.29	.42	.91**	.05	.34	.17
CD	.	.87**	.90**	.85**	-.09	.04	.75*	.96**	.64	.55	.78**	-.01	.74*	.95**	.51	.71*	-.16	.29	1.00	.94**	.22	.05	.46	.21
SN	.	.86**	.87**	.80**	.01	.04	.68*	.90**	.71*	.62	.69*	-.01	.73*	.95**	.48	.70*	-.12	.42	.94**	1.00	.33	-.05	.40	.08
PB	.95	.15	-.04	.18	-.22	-.21	-.20	.09	.84**	.66*	.77**	.85**	.01	.74**	.77**	.17	.53	.91**	.22	.33	1.00	-.42	.63*	-.28
OC	-.76	-.30	-.41	-.27	.08	.05	.16	-.43	-.59	-.23	-.58	-.28	-.46	-.53	-.48	-.28	-.64	.05	.05	-.05	-.42	1.00	-.16	.99**
EC	.72	.25	.11	.22	-.27	-.16	.28	.28	.46	.34	.40	.46	.11	.51	.41	.67*	.32	.34	.46	.40	.63*	-.16	1.00	-.04
TC	-.69	-.27	-.40	-.21	.04	.03	.19	-.40	-.51	-.15	-.52	-.22	-.46	-.44	-.41	-.11	-.61	.17	.21	.08	-.28	.99**	-.04	1.00

2-tailed Signif: * - .01 ** - .001

F.6.2 Broadcast Burns -- Smoldering (p.2 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFEFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.76	.72	-.69	-.79	-.47	-.88	-.80	.63	-.47	-.54	-.53	-.82	-.86	-.83	-.81	-.77	-.78	-.86	-.90
AL	-.30	.25	-.27	-.22	.19	-.25	-.13	-.17	.19	-.07	-.06	-.07	-.09	-.28	-.26	-.23	-.22	-.23	-.23
SI	-.41	.11	-.40	-.27	.10	-.13	-.01	-.13	.10	-.01	-.04	-.13	-.18	-.30	-.25	-.28	-.26	-.26	-.26
P	-.27	.22	-.21	.00	.17	-.26	-.26	-.14	.17	-.12	-.07	.19	.10	-.12	-.13	.03	.00	-.01	-.04
S	.08	-.27	.04	-.10	.18	-.10	-.24	-.21	.18	.10	.33	-.16	-.18	-.10	-.23	-.14	-.10	-.08	.02
CL	.05	-.16	.03	.07	.22	.09	-.15	-.31	.22	-.03	.16	.23	.25	.16	-.04	-.08	.08	.02	.13
K	.16	.28	.19	-.02	.29	.11	-.00	-.41	.29	.06	.07	.14	.20	.04	-.10	-.15	-.00	-.04	-.02
CA	-.43	.28	-.40	-.12	.08	-.16	-.06	-.05	.08	.00	-.06	-.06	-.11	-.17	-.11	-.09	-.12	-.11	-.16
TI	-.59	.46	-.51	-.11	-.28	-.29	-.27	.56	-.28	-.20	-.47	-.17	-.20	-.20	-.16	.09	-.14	-.13	-.27
V	-.23	.34	-.15	.01	-.33	-.20	-.21	.56	-.33	-.05	.00	-.13	-.12	-.08	-.09	.45	-.05	.05	.08
CR	-.58	.40	-.52	-.00	-.26	-.31	-.27	.56	-.26	-.22	-.51	-.02	-.09	-.10	-.06	.20	-.03	-.03	-.19
MN	-.28	.46	-.22	.05	-.00	-.34	-.28	.19	-.00	-.24	-.41	.14	.11	-.09	-.02	.12	.04	.03	-.09
FE	-.46	.11	-.46	-.24	.11	-.21	-.08	-.06	.11	-.16	-.23	-.13	-.25	-.30	-.19	-.23	-.24	-.26	-.31
NI	-.53	.51	-.44	-.08	-.14	-.34	-.31	.40	-.14	-.23	-.45	-.07	-.07	-.22	-.18	.25	-.11	-.11	-.26
CU	-.48	.41	-.41	-.02	-.27	-.30	-.28	.57	-.27	-.24	-.46	-.11	-.13	-.16	-.14	.38	-.07	-.08	-.23
ZN	-.28	.67*	-.11	-.15	.23	.01	-.06	-.22	.23	-.25	-.43	.05	.07	-.04	-.13	-.20	-.14	-.22	-.31
BR	-.64	.32	-.61	.23	-.07	-.23	-.29	.25	-.07	-.17	-.15	.32	.25	.11	.08	.39	.20	.18	.16
AG	.05	.34	.17	.16	.17	-.37	-.32	-.11	.17	-.09	-.05	.21	.31	-.10	-.01	.22	.15	.21	.17
CD	.05	.46	.21	-.16	.01	-.13	-.03	.01	.01	.14	.08	-.01	-.00	-.24	-.17	-.13	-.17	-.08	-.14
SN	-.05	.40	.08	-.19	.17	-.25	-.19	-.16	.17	-.02	.04	-.13	-.06	-.27	-.23	-.19	-.18	-.14	-.15
PB	-.42	.63*	-.28	-.07	-.12	-.33	-.33	.37	-.12	-.27	-.45	.07	.11	-.17	-.15	.08	-.09	-.09	-.20
OC	1.00	-.16	.99**	.15	.31	.09	.08	-.48	.31	.56	.62*	-.21	.08	.19	-.06	.04	.16	.27	.37
EC	-.16	1.00	-.04	-.23	-.07	.25	.20	.10	-.07	-.09	-.42	-.27	-.19	-.11	-.19	-.14	-.24	-.30	-.44
TC	.99**	-.04	1.00	.12	.30	.13	.12	-.48	.30	.55	.58*	-.26	.06	.18	-.09	.02	.13	.23	.32

2-tailed Signif: * - .01 ** - .001

F.6.3 Broadcast Burns -- Smoldering (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.76	-.30	-.41	-.27	.08	.05	.16	-.43	-.59	-.23	-.58	-.28	-.46	-.53	-.48	-.28	-.64	.05	.05	-.05	-.42	1.00	-.16	.99**
EC	.72	.25	.11	.22	-.27	-.16	.28	.28	.46	.34	.40	.46	.11	.51	.41	.67*	.32	.34	.46	.40	.63*	-.16	1.00	-.04
TC	-.69	-.27	-.40	-.21	.04	.03	.19	-.40	-.51	-.15	-.52	-.22	-.46	-.44	-.41	-.11	-.61	.17	.21	.08	-.28	.99**	-.04	1.00
CARBON	-.79	-.22	-.27	.00	-.10	.07	-.02	-.12	-.11	.01	-.00	.05	-.24	-.08	-.02	-.15	.23	.16	-.16	-.19	-.07	.15	-.23	.12
CMBSTEFF	-.47	.19	.10	.17	.18	.22	.29	.08	-.28	-.33	-.26	-.00	.11	-.14	-.27	.23	-.07	.17	.01	.17	-.12	.31	-.07	.30
EFPM	-.88	-.25	-.13	-.26	-.10	.09	.11	-.16	-.29	-.20	-.31	-.34	-.21	-.34	-.30	.01	-.23	-.37	-.13	-.25	-.33	.09	.25	.13
EFPM2.5	-.80	-.13	-.01	-.26	-.24	-.15	-.00	-.06	-.27	-.21	-.27	-.28	-.08	-.31	-.28	-.06	-.29	-.32	-.03	-.19	-.33	.08	.20	.12
EFCO	.63	-.17	-.13	-.14	-.21	-.31	-.41	-.05	.56	.56	.56	.19	-.06	.40	.57	-.22	.25	-.11	.01	-.16	.37	-.48	.10	-.48
EFCO2	-.47	.19	.10	.17	.18	.22	.29	.08	-.28	-.33	-.26	-.00	.11	-.14	-.27	.23	-.07	.17	.01	.17	-.12	.31	-.07	.30
EFCH4	-.54	-.07	-.01	-.12	.10	-.03	.06	.00	-.20	-.05	-.22	-.24	-.16	-.23	-.24	-.25	-.17	-.09	.14	-.02	-.27	.56	-.09	.55
EFNMHC	-.53	-.06	-.04	-.07	.33	.16	.07	-.06	-.47	.00	-.51	-.41	-.23	-.45	-.46	-.43	-.15	-.05	.08	.04	-.45	.62*	-.42	.58*
W_FLUX	-.82	-.07	-.13	.19	-.16	.23	.14	-.06	-.17	-.13	-.02	.14	-.13	-.07	-.11	.05	.32	.21	-.01	-.13	.07	-.21	-.27	-.26
I_R	-.86	-.09	-.18	.10	-.18	.25	.20	-.11	-.20	-.12	-.09	.11	-.25	-.07	-.13	.07	.25	.31	-.00	-.06	.11	.08	-.19	.06
C_PM	-.83	-.28	-.30	-.12	-.10	.16	.04	-.17	-.20	-.08	-.10	-.09	-.30	-.22	-.16	-.04	.11	-.10	-.24	-.27	-.17	.19	-.11	.18
C_PM2.5	-.81	-.26	-.25	-.13	-.23	-.04	-.10	-.11	-.16	-.09	-.06	-.02	-.19	-.18	-.14	-.13	.08	-.01	-.17	-.23	-.15	-.06	-.19	-.09
CO_PPM	-.77	-.23	-.28	.03	-.14	-.08	-.15	-.09	.09	.45	.20	.12	-.23	.25	.38	-.20	.39	.22	-.13	-.19	.08	.04	-.14	.02
CO2_PPM	-.78	-.22	-.26	.00	-.10	.08	-.00	-.12	-.14	-.05	-.03	.04	-.24	-.11	-.07	-.14	.20	.15	-.17	-.18	-.09	.16	-.24	.13
CH4_PPM	-.86	-.23	-.26	-.01	-.08	.02	-.04	-.11	-.13	.05	-.03	.03	-.26	-.11	-.08	-.22	.18	.21	-.08	-.14	-.09	.27	-.30	.23
NMHC_PPM	-.90	-.23	-.26	-.04	.02	.13	-.02	-.16	-.27	.08	-.19	-.09	-.31	-.26	-.23	-.31	.16	.17	-.14	-.15	-.20	.37	-.44	.32

2-tailed Signif: * - .01 ** - .001

F.6.4 Broadcast Burns -- Smoldering (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	-.16	.99**	.15	.31	.09	.08	-.48	.31	.56	.62*	-.21	.08	.19	-.06	.04	.16	.27	.37
EC	-.16	1.00	-.04	-.23	-.07	.25	.20	.10	-.07	-.09	-.42	-.27	-.19	-.11	-.19	-.14	-.24	-.30	-.44
TC	.99**	-.04	1.00	.12	.30	.13	.12	-.48	.30	.55	.58*	-.26	.06	.18	-.09	.02	.13	.23	.32
CARBON	.15	-.23	.12	1.00	.32	-.26	-.28	-.20	.32	-.10	.00	.76**	.68**	.92**	.95**	.95**	.00**	.97**	.89**
CMBSTEFF	.31	-.07	.30	.32	1.00	-.58*	-.66**	-.93**	1.00**	-.30	.01	.32	.28	.26	.18	.12	.35	.32	.34
EFPM	.09	.25	.13	-.26	-.58*	1.00	.89**	.31	-.58*	.46	.19	-.30	-.22	.02	-.08	-.23	-.27	-.28	-.27
EFPM2.5	.08	.20	.12	-.28	-.66**	.89**	1.00	.39	-.66**	.65**	.19	-.37	-.33	-.05	-.05	-.22	-.29	-.26	-.30
EFCO	-.48	.10	-.48	-.20	-.93**	.31	.39	1.00	-.93**	.08	-.20	-.23	-.22	-.20	-.07	.05	-.24	-.23	-.30
EFCO2	.31	-.07	.30	.32	1.00**	-.58*	-.66**	-.93**	1.00	-.30	.01	.32	.28	.26	.18	.12	.35	.32	.34
EFCH4	.56	-.09	.55	-.10	-.30	.46	.65**	.08	-.30	1.00	.62*	-.33	-.24	-.10	-.24	-.09	-.10	.04	.04
EFNMHC	.62*	-.42	.58*	.00	.01	.19	.19	-.20	.01	.62*	1.00	-.22	-.17	.03	-.12	-.05	.00	.13	.39
W_FLUX	-.21	-.27	-.26	.76**	.32	-.30	-.37	-.23	.32	-.33	-.22	1.00	.88**	.66**	.66**	.65*	.78**	.72**	.65*
I_R	.08	-.19	.06	.68**	.28	-.22	-.33	-.22	.28	-.24	-.17	.88**	1.00	.61*	.55	.52	.70**	.65*	.63*
C_PM	.19	-.11	.18	.92**	.26	.02	-.05	-.20	.26	-.10	.03	.66**	.61*	1.00	.96**	.87**	.92**	.88**	.82**
C_PM2.5	-.06	-.19	-.09	.95**	.18	-.08	-.05	-.07	.18	-.24	-.12	.66**	.55	.96**	1.00	.92**	.94**	.91**	.81**
CO_PPM	.04	-.14	.02	.95**	.12	-.23	-.22	.05	.12	-.09	-.05	.65*	.52	.87**	.92**	1.00	.94**	.92**	.81**
CO2_PPM	.16	-.24	.13	.00**	.35	-.27	-.29	-.24	.35	-.10	.00	.78**	.70**	.92**	.94**	.94**	1.00	.97**	.89**
CH4_PPM	.27	-.30	.23	.97**	.32	-.28	-.26	-.23	.32	.04	.13	.72**	.65*	.88**	.91**	.92**	.97**	1.00	.93**
NMHC_PPM	.37	-.44	.32	.89**	.34	-.27	-.30	-.30	.34	.04	.39	.65*	.63*	.82**	.81**	.81**	.89**	.93**	1.00

2-tailed Signif: * - .01 ** - .001

F.7.1 Broadcast Burns -- Flaming and Smoldering (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AC	CD	SN	PB	OC	EC	TC
NA	1.00	.15	.08	.	-.01	-.05	-.07	-.09	.11	-.02	.05	.42	.03	.20	.20	.09	-.02	.	.	.	.16	-.41	.25	-.67
AL	.15	1.00	.87**	.75**	.26	.18	.31	.27	.09	.10	.26	.47**	.88**	.91**	.87**	.16	.75**	.90**	.96**	.95**	.83**	-.25	.19	-.10
SI	.08	.87**	1.00	.83**	.19	.15	.24	.54**	-.05	-.03	.10	.26	.80**	.69**	.65**	.30	.63**	.64**	.79**	.85**	.66**	-.07	-.08	-.15
P	.	.75**	.83**	1.00	.31	.28	.52*	.58*	.77**	.47	.71**	.71**	.73**	.71**	.75**	.70**	.81**	.62**	.68**	.73**	.84**	-.43	.90**	.79**
S	-.01	.26	.19	.31	1.00	.65**	.63**	-.03	-.10	-.02	.05	.10	.11	.18	.20	.41	.45*	.21	.16	.15	.18	.04	.25	.30
CL	-.05	.18	.15	.28	.65**	1.00	.81**	-.06	-.16	-.08	-.04	.07	.01	.08	.19	.45*	.56**	.10	.05	.03	.08	.04	.29	.32
K	-.07	.31	.24	.52*	.63**	.81**	1.00	.14	.03	.12	.18	.33	.18	.23	.28	.83**	.61**	.29	.28	.21	.28	-.16	.66**	.48*
CA	-.09	.27	.54**	.58*	-.03	-.06	.14	1.00	.09	.07	.07	.26	.25	.00	.01	.57**	.08	-.11	.09	.21	.16	-.30	.20	-.14
TI	.11	.09	-.05	.77**	-.10	-.16	.03	.09	1.00	.91**	.91**	.72**	.42*	.20	.26	.22	.12	.88**	.87**	.88**	.35	-.66**	.42	-.37
V	-.02	.10	-.03	.47	-.02	-.08	.12	.07	.91**	1.00	.97**	.57**	.45*	.16	.21	.27	.12	.80**	.76**	.75**	.30	-.50*	.38	-.20
CR	.05	.26	.10	.71**	.05	-.04	.18	.07	.91**	.97**	1.00	.66**	.59**	.33	.37	.31	.27	.96**	.96**	.92**	.45*	-.55*	.43	-.21
MN	.42	.47**	.26	.71**	.10	.07	.33	.26	.72**	.57**	.66**	1.00	.54**	.53**	.57**	.39	.51*	.75**	.68**	.63**	.66**	-.68**	.62**	-.15
FE	.03	.88**	.80**	.73**	.11	.01	.18	.25	.42*	.45*	.59**	.54**	1.00	.85**	.82**	.21	.66**	.85**	.93**	.93**	.83**	-.43*	.20	-.29
NI	.20	.91**	.69**	.71**	.18	.08	.23	.00	.20	.16	.33	.53**	.85**	1.00	.97**	.15	.80**	.95**	.96**	.92**	.94**	-.56*	.31	-.37
CU	.20	.87**	.65**	.75**	.20	.19	.28	.01	.26	.21	.37	.57**	.82**	.97**	1.00	.23	.86**	.92**	.91**	.89**	.94**	-.50*	.35	-.24
ZN	.09	.16	.30	.70**	.41	.45*	.83**	.57**	.22	.27	.31	.39	.21	.15	.23	1.00	.49*	.08	.09	.14	.40	-.41	.80**	.45
BR	-.02	.75**	.63**	.81**	.45*	.56**	.61**	.08	.12	.12	.27	.51*	.66**	.80**	.86**	.49*	1.00	.77**	.72**	.72**	.85**	-.39	.47*	.06
AC	.	.90**	.64**	.62**	.21	.10	.29	-.11	.88**	.80**	.96**	.75**	.85**	.95**	.92**	.08	.77**	1.00	.94**	.91**	.90**	-.16	.38	.35
CD	.	.96**	.79**	.68**	.16	.05	.28	.09	.87**	.76**	.96**	.68**	.93**	.96**	.91**	.09	.72**	.94**	1.00	.95**	.88**	-.23	.70**	.68**
SN	.	.95**	.85**	.73**	.15	.03	.21	.21	.88**	.75**	.92**	.63**	.93**	.92**	.89**	.14	.72**	.91**	.95**	1.00	.86**	-.07	.16	.14
PB	.16	.83**	.66**	.84**	.18	.08	.28	.16	.35	.30	.45*	.66**	.83**	.94**	.94**	.40	.85**	.90**	.88**	.86**	1.00	-.66**	.50*	-.26
OC	-.41	-.25	-.07	-.43	.04	.04	-.16	-.30	-.66**	-.50*	-.55*	-.68**	-.43*	-.56*	-.50*	-.41	-.39	-.16	-.23	-.07	-.66**	1.00	-.57**	.57**
EC	.25	.19	-.08	.90**	.25	.29	.66**	.20	.42	.38	.43	.62**	.20	.31	.35	.80**	.47*	.38	.70**	.16	.50*	-.57**	1.00	.35
TC	-.67	-.10	-.15	.79**	.30	.32	.48*	-.14	-.37	-.20	-.21	-.15	-.29	-.37	-.24	.45	.06	.35	.68**	.14	-.26	.57**	.35	1.00

2-tailed Signif: * - .01 ** - .001

F.7.2 Broadcast Burns -- Flaming and Smoldering (p.2 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.41	.25	-.67	-.27	.34	-.25	-.24	-.34	.34	-.32	-.15	-.57	-.16	-.46	-.44	-.52	-.24	-.52	-.43
AL	-.25	.19	-.10	-.11	.14	-.06	-.10	-.16	.14	-.14	-.05	-.18	-.12	-.10	-.17	-.23	-.10	-.24	-.17
SI	-.07	-.08	-.15	-.20	.04	-.04	-.03	-.08	.03	-.05	.00	-.14	-.13	-.24	-.24	-.31	-.19	-.28	-.23
P	-.43	.90**	.79**	.03	.37	-.29	-.35	-.38	.37	-.39	-.37	-.20	.08	-.11	-.14	-.27	.04	-.31	-.23
S	.04	.25	.30	.25	.45*	-.29	-.44*	-.49**	.45*	-.34	-.15	-.22	.30	.12	-.02	-.13	.26	-.10	.09
CL	.04	.29	.32	.29	.47**	-.24	-.34	-.50**	.48**	-.44*	-.32	-.14	.32	.20	.15	-.04	.30	-.01	.18
K	-.16	.65**	.48*	.45*	.68**	-.38	-.54**	-.71**	.69**	-.63**	-.54**	-.22	.51**	.27	.13	-.09	.47**	-.12	.10
CA	-.30	.20	-.14	.12	.15	-.22	-.18	-.13	.15	-.12	-.18	-.01	.12	.05	.02	-.03	.13	-.08	-.07
TI	-.66**	.42	-.37	.23	.15	-.29	-.30	-.01	.15	-.20	-.29	-.15	.12	-.03	-.16	.05	.24	-.11	-.08
V	-.50*	.38	-.20	.24	.17	-.22	-.25	-.09	.16	-.18	-.18	-.10	.10	.01	-.15	.05	.26	-.10	-.01
CR	-.55*	.43	-.21	.24	.24	-.23	-.28	-.17	.24	-.25	-.25	-.13	.10	-.01	-.16	-.02	.26	-.14	-.04
MN	-.68**	.62**	-.15	.23	.37*	-.39*	-.47*	-.28	.36	-.39*	-.44*	-.16	.18	.06	-.07	-.05	.25	-.14	-.11
FE	-.43*	.20	-.29	-.12	.07	-.06	-.09	-.07	.07	-.11	-.07	-.17	-.16	-.21	-.24	-.23	-.10	-.26	-.21
NI	-.56*	.31	-.37	-.07	.13	-.03	-.10	-.13	.13	-.19	-.10	-.23	-.08	-.06	-.13	-.15	-.07	-.20	-.13
CU	-.50*	.35	-.24	-.05	.16	-.09	-.15	-.15	.16	-.24	-.16	-.27	-.09	-.08	-.13	-.14	-.04	-.21	-.12
ZN	-.41	.80**	.45	.33	.61**	-.47*	-.54**	-.60**	.61**	-.63**	-.64**	-.19	.43	.11	.03	-.18	.35	-.29	-.14
BR	-.39	.47*	.06	.17	.40	-.26	-.33	-.41	.40	-.45*	-.35	-.25	.12	.05	.01	-.10	.18	-.17	-.03
AG	-.16	.38	.35	-.11	.18	-.08	-.16	-.20	.18	-.21	-.11	-.21	-.11	-.02	-.13	-.20	-.11	-.20	-.14
CD	-.23	.70**	.68**	-.14	.12	-.01	-.07	-.15	.12	-.15	-.06	-.22	-.10	-.06	-.12	-.23	-.13	-.22	-.16
SN	-.07	.16	.14	-.17	.13	-.05	-.11	-.15	.13	-.13	-.03	-.26	-.18	-.12	-.22	-.26	-.16	-.22	-.17
PB	-.66**	.50*	-.26	.04	.26	-.17	-.25	-.24	.26	-.32	-.26	-.23	.08	-.04	-.14	-.14	.06	-.23	-.15
OC	1.00	-.57**	.57**	-.35	-.32	.35	.41	.19	-.32	.50*	.55**	.20	-.22	-.20	-.16	-.10	-.36	.08	.05
EC	-.57**	1.00	.35	.42*	.67**	-.48*	-.61**	-.63**	.67**	-.61**	-.60**	-.28	.47*	.16	-.06	-.11	.45*	-.14	.00
TC	.57**	.35	1.00	.02	.30	-.07	-.16	-.41*	.30	-.04	.03	-.06	.25	-.07	-.26	-.22	.03	-.05	.06

2-tailed Signif: * - .01 ** - .001

F.7.3 Broadcast Burns -- Flaming and Smoldering (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.41	-.25	-.07	-.43	.04	.04	-.16	-.30	-.66**	-.50*	-.55*	-.68**	-.43*	-.56*	-.50*	-.41	-.39	-.16	-.23	-.07	-.66**	1.00	-.57**	.57**
EC	.25	.19	-.08	.90**	.25	.29	.66**	.20	.42	.38	.43	.62**	.20	.31	.35	.80**	.47*	.38	.70**	.16	.50*	-.57**	1.00	.35
TC	-.67	-.10	-.15	.79**	.30	.32	.48*	-.14	-.37	-.20	-.21	-.15	-.29	-.37	-.24	.45	.06	.35	.68**	.14	-.26	.57**	.35	1.00
CARBON	-.27	-.11	-.20	.03	.25	.29	.45*	.12	.23	.24	.24	.23	-.12	-.07	-.05	.33	.17	-.11	-.14	-.17	.04	-.35	.42*	.02
CMBSTEFF	.34	.14	.04	.37	.45*	.47**	.68**	.15	.15	.17	.24	.37*	.07	.13	.16	.61**	.40	.18	.12	.13	.26	-.32	.67**	.30
EFPM	-.25	-.06	-.04	-.29	-.29	-.24	-.38	-.22	-.29	-.22	-.23	-.39*	-.06	-.03	-.09	-.47*	-.26	-.08	-.01	-.05	-.17	.35	-.48*	-.07
EFPM2.5	-.24	-.10	-.03	-.35	-.44*	-.34	-.54**	-.18	-.30	-.25	-.28	-.47*	-.09	-.10	-.15	-.54**	-.33	-.16	-.07	-.11	-.25	.41	-.61**	-.16
EFCO	-.34	-.16	-.08	-.38	-.49**	-.50**	-.71**	-.13	-.01	-.09	-.17	-.28	-.07	-.13	-.15	-.60**	-.41	-.20	-.15	-.15	-.24	.19	-.63**	-.41*
EFCO2	.34	.14	.03	.37	.45*	.48**	.69**	.15	.15	.16	.24	.36	.07	.13	.16	.61**	.40	.18	.12	.13	.26	-.32	.67**	.30
EFCH4	-.32	-.14	-.05	-.39	-.34	-.44*	-.63**	-.12	-.20	-.18	-.25	-.39*	-.11	-.19	-.24	-.63**	-.45*	-.21	-.15	-.13	-.32	.50*	-.61**	-.04
EFNMHC	-.15	-.05	.00	-.37	-.15	-.32	-.54**	-.18	-.29	-.18	-.25	-.44*	-.07	-.10	-.16	-.64**	-.35	-.11	-.06	-.03	-.26	.55**	-.60**	.03
W_FLUX	-.57	-.18	-.14	.20	-.22	-.14	-.22	-.01	-.15	-.10	-.13	-.16	-.17	-.23	-.27	-.19	-.25	-.21	-.22	-.26	-.23	.20	-.28	-.06
I_R	-.16	-.12	-.13	.08	.30	.32	.51**	.12	.12	.10	.10	.18	-.16	-.08	-.09	.43	.12	-.11	-.10	-.18	.08	-.22	.47*	.25
C_PM	-.46	-.10	-.24	-.11	.12	.20	.27	.05	-.03	.01	-.01	.06	-.21	-.06	-.08	.11	.05	-.02	-.06	-.12	-.04	-.20	.16	-.07
C_PM2.5	-.44	-.17	-.24	-.14	-.02	.15	.13	.02	-.16	-.15	-.16	-.07	-.24	-.13	-.13	.03	.01	-.13	-.12	-.22	-.14	-.16	-.06	-.26
CO_PPM	-.52	-.23	-.31	-.27	-.13	-.04	-.09	-.03	.05	.05	-.02	-.05	-.23	-.15	-.14	-.18	-.10	-.20	-.23	-.26	-.14	-.10	-.11	-.22
CO2_PPM	-.24	-.10	-.19	.04	.26	.30	.47**	.13	.24	.26	.26	.25	-.10	-.07	-.04	.35	.18	-.11	-.13	-.16	.06	-.36	.45*	.03
CH4_PPM	-.52	-.24	-.28	-.31	-.10	-.01	-.12	-.08	-.11	-.10	-.14	-.14	-.26	-.20	-.21	-.29	-.17	-.20	-.22	-.22	-.23	.08	-.14	-.05
NMHC_PPM	-.43	-.17	-.23	-.23	.09	.18	.10	-.07	-.08	-.01	-.04	-.11	-.21	-.13	-.12	-.14	-.03	-.14	-.16	-.17	-.15	.05	.00	.06

2-tailed Signif: * - .01 ** - .001

F.7.4 Broadcast Burns -- Flaming and Smoldering (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	-.57**	.57**	-.35	-.32	.35	.41	.19	-.32	.50*	.55**	.20	-.22	-.20	-.16	-.10	-.36	.08	.05
EC	-.57**	1.00	.35	.42*	.67**	-.48*	-.61**	-.63**	.67**	-.61**	-.60**	-.28	.47*	.16	-.06	-.11	.45*	-.14	.00
TC	.57**	.35	1.00	.02	.30	-.07	-.16	-.41*	.30	-.04	.03	-.06	.25	-.07	-.26	-.22	.03	-.05	.06
CARBON	-.35	.42*	.02	1.00	.65**	-.51**	-.59**	-.58**	.65**	-.57**	-.52**	.08	.77**	.76**	.58**	.65**	.00**	.57**	.73**
CMBSTEFF	-.32	.67**	.30	.65**	1.00	-.70**	-.81**	-.97**	.00**	-.81**	-.65**	-.23	.60**	.46*	.23	.11	.67**	.08	.29
EFPM	.35	-.48*	-.07	-.51**	-.70**	1.00	.91**	.58**	-.69**	.64**	.51**	-.03	-.43*	-.15	-.06	-.20	-.51**	-.15	-.27
EFPM2.5	.41	-.61**	-.16	-.59**	-.81**	.91**	1.00	.73**	-.81**	.78**	.61**	.02	-.53**	-.21	-.02	-.08	-.60**	-.05	-.26
EFCO	.19	-.63**	-.41*	-.58**	-.97**	.58**	.73**	1.00	-.98**	.73**	.55**	.26	-.57**	-.40*	-.16	-.01	-.60**	-.03	-.26
EFCO2	-.32	.67**	.30	.65**	.00**	-.69**	-.81**	-.98**	1.00	-.81**	-.64**	-.23	.60**	.46*	.23	.11	.67**	.08	.29
EFCH4	.50*	-.61**	-.04	-.57**	-.81**	.64**	.78**	.73**	-.81**	1.00	.84**	.20	-.56**	-.39*	-.28	-.06	-.59**	.08	-.14
EFNMHC	.55**	-.60**	.03	-.52**	-.65**	.51**	.61**	.55**	-.64**	.84**	1.00	.18	-.55**	-.33	-.24	-.07	-.53**	.12	.03
W_FLUX	.20	-.28	-.06	.08	-.23	-.03	.02	.26	-.23	.20	.18	1.00	.15	.28	.32	.56**	.04	.60**	.38
I_R	-.22	.47*	.25	.77**	.60**	-.43*	-.53**	-.57**	.60**	-.56**	-.55**	.15	1.00	.55**	.36	.29	.77**	.27	.46*
C_PM	-.20	.16	-.07	.76**	.46*	-.15	-.21	-.40*	.46*	-.39*	-.33	.28	.55**	1.00	.90**	.76**	.73**	.66**	.76**
C_PM2.5	-.16	-.06	-.26	.58**	.23	-.06	-.02	-.16	.23	-.28	-.24	.32	.36	.90**	1.00	.81**	.55**	.70**	.70**
CO_PPM	-.10	-.11	-.22	.65**	.11	-.20	-.08	-.01	.11	-.06	-.07	.56**	.29	.76**	.81**	1.00	.61**	.90**	.77**
CO2_PPM	-.36	.45*	.03	.00**	.67**	-.51**	-.60**	-.60**	.67**	-.59**	-.53**	.04	.77**	.73**	.55**	.61**	1.00	.53**	.70**
CH4_PPM	.08	-.14	-.05	.57**	.08	-.15	-.05	-.03	.08	.08	.12	.60**	.27	.66**	.70**	.90**	.53**	1.00	.91**
NMHC_PPM	.05	.00	.06	.73**	.29	-.27	-.26	-.26	.29	-.14	.03	.38	.46*	.76**	.70**	.77**	.70**	.91**	1.00

2-tailed Signif: * - .01 ** - .001

F.8.1 Broadcast Burns -- Fire Average (p.1 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	BC	TC
NA	1.00	.37	.97	.	.24	-.31	-.73	-.38	.46	-.11	-.39	.41	.91	.23	.23	-.09	.98	.	.	.	.18	-.71	.14	-.95
AL	.37	1.00	.96**	.97**	.41	.78**	.70**	.84**	-.08	-.07	-.00	.28	.90**	.65*	.30	.60	.56	.41	.87**	.86**	.46	-.38	-.11	-.38
SI	.97	.96**	1.00	.97**	.41	.85**	.81**	.90**	-.09	-.08	-.01	.14	.90**	.65*	.26	.68*	.47	.31	.94**	.93**	.42	-.29	-.15	-.30
P	.	.97**	.97**	1.00	.30	.90**	.89**	.94**	.93**	.57	.85**	.37	.95**	.91**	.73*	.71*	.55	.40	.94**	.90**	.78*	0	.63	.39
S	.24	.41	.41	.30	1.00	.53	.30	.24	-.29	-.27	-.35	-.33	.24	.07	-.18	.13	.22	.34	.25	.44	-.02	.16	-.31	.08
CL	-.31	.78**	.85**	.90**	.53	1.00	.87**	.75**	-.25	-.19	-.19	-.16	.60*	.49	.13	.64*	.48	.23	.88**	.87**	.24	-.08	-.20	-.11
K	-.73	.70**	.81**	.89**	.30	.87**	1.00	.83**	-.19	-.10	-.15	-.08	.57*	.53	.08	.90**	.33	.28	.96**	.87**	.33	.05	.45	.14
CA	-.38	.84**	.90**	.94**	.24	.75**	.83**	1.00	.11	.10	.19	.20	.79**	.68*	.34	.77**	.25	.25	.99**	.95**	.47	-.15	.30	-.08
TI	.46	-.08	-.09	.93**	-.29	-.25	-.19	.11	1.00	.74**	.89**	.65*	.09	.60	.81**	-.08	.13	.54	.86**	.77*	.71*	-.77*	.42	-.49
V	-.11	-.07	-.08	.57	-.27	-.19	-.10	.10	.74**	1.00	.65*	.37	.02	.48	.63*	.01	.04	.24	.68	.44	.60	-.47	.35	-.24
CR	-.39	-.00	-.01	.85**	-.35	-.19	-.15	.19	.89**	.65*	1.00	.69*	.16	.56	.77**	-.10	.07	.38	.66	.62	.65*	-.61	.33	-.40
MN	.41	.28	.14	.37	-.33	-.16	-.08	.20	.65*	.37	.69*	1.00	.44	.56	.65*	.07	.47	.52	.15	-.02	.71*	-.10	.51	.01
FE	.91	.90**	.90**	.95**	.24	.60*	.57*	.79**	.09	.02	.16	.44	1.00	.75**	.37	.62*	.63*	.41	.87**	.85**	.57	-.18	-.05	-.18
NI	.23	.65*	.65*	.91**	.07	.49	.53	.68*	.60	.48	.56	.56	.75**	1.00	.81**	.55	.53	.35	.81**	.78*	.93**	-.66*	.64	-.26
CU	.23	.30	.26	.73*	-.18	.13	.08	.34	.81**	.63*	.77**	.65*	.37	.81**	1.00	.09	.35	.17	.53	.56	.78**	-.62	.54	-.28
ZN	-.09	.60	.68*	.71*	.13	.64*	.90**	.77**	-.08	.01	-.10	.07	.62*	.55	.09	1.00	.21	.26	.80**	.71*	.44	.14	.68*	.54
BR	.98	.56	.47	.55	.22	.48	.33	.25	.13	.04	.07	.47	.63*	.53	.35	.21	1.00	.46	.33	.24	.52	-.41	.13	-.32
AG	.	.41	.31	.40	.34	.23	.28	.25	.54	.24	.38	.52	.41	.35	.17	.26	.46	1.00	.33	.29	.52	-.14	.25	.06
CD	.	.87**	.94**	.94**	.25	.88**	.96**	.99**	.86**	.68	.66	.15	.87**	.81**	.53	.80**	.33	.33	1.00	.94**	.66	.07	.63	.44
SN	.	.86**	.93**	.90**	.44	.87**	.87**	.95**	.77*	.44	.62	-.02	.85**	.78*	.56	.71*	.24	.29	.94**	1.00	.58	-.01	.22	.13
PB	.18	.46	.42	.78*	-.02	.24	.33	.47	.71*	.60	.65*	.71*	.57	.93**	.78**	.44	.52	.52	.66	.58	1.00	-.63	.59	-.26
OC	-.71	-.38	-.29	0	.16	-.08	.05	-.15	-.77*	-.47	-.61	-.10	-.18	-.66*	-.62	.14	-.41	-.14	.07	-.01	-.63	1.00	.23	.98**
BC	.14	-.11	-.15	.63	-.31	-.20	.45	.30	.42	.35	.33	.51	-.05	.64	.54	.68*	.13	.25	.63	.22	.59	.23	1.00	.43
TC	-.95	-.38	-.30	.39	.08	-.11	.14	-.08	-.49	-.24	-.40	.01	-.18	-.26	-.28	.54	-.32	.06	.44	.13	-.26	.98**	.43	1.00

2-tailed Signif: * - .01 ** - .001

F.8.2 Broadcast Burns -- Fire Average (p.2 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	BFPM	BFPM2.5	BFCO	BFCO2	BFCH4	BFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
NA	-.71	.14	-.95	-.92	-.46	.63	.52	.40	-.46	.76	.46	-.99	.	-.94	-.99	-.96	-.91	-.95	-.69
AL	-.38	-.11	-.38	-.19	.05	-.25	-.07	-.05	.05	-.13	-.08	-.04	.	-.34	-.24	-.21	-.18	-.25	-.21
SI	-.29	-.15	-.30	-.22	.10	-.20	-.05	-.13	.10	-.08	-.05	-.08	.	-.34	-.27	-.27	-.21	-.26	-.23
P	0	.63	.39	-.17	.07	-.36	-.34	-.02	.07	-.03	-.08	.12	.	-.40	-.35	-.17	-.16	-.16	-.22
S	.16	-.31	.08	.11	.32	-.08	-.25	-.36	.32	-.04	.27	-.09	.	.06	-.02	-.16	.14	.09	.24
CL	-.08	-.20	-.11	-.22	.15	-.02	-.08	-.28	.15	.01	.07	.05	.	-.22	-.26	-.32	-.20	-.18	-.14
K	.05	.45	.14	-.17	.37	-.17	-.20	-.44	.37	-.19	-.16	.02	.	-.27	-.29	-.33	-.15	-.26	-.24
CA	-.15	.30	-.08	-.07	.18	-.35	-.17	-.11	.18	-.13	-.16	-.01	.	-.25	-.15	-.07	-.06	-.12	-.15
TI	-.77*	.42	-.49	.13	-.20	-.28	-.21	.53	-.20	.10	-.21	-.18	.	-.04	-.05	.36	.11	.14	-.01
V	-.47	.35	-.24	.32	-.13	-.18	-.24	.37	-.13	-.01	-.05	-.10	.	.18	.06	.51	.31	.29	.31
CR	-.61	.33	-.40	.20	-.31	-.30	-.22	.64*	-.31	.11	-.21	.00	.	.05	.10	.54	.17	.27	.06
MN	-.10	.51	.01	-.01	-.10	-.45	-.24	.29	-.10	-.08	-.31	.08	.	-.26	-.15	.15	-.02	-.04	-.20
PB	-.18	-.05	-.18	-.21	.01	-.28	.01	.04	.01	-.09	-.12	-.09	.	-.38	-.24	-.20	-.21	-.27	-.28
NI	-.66*	.64	-.26	-.01	.13	-.35	-.42	.05	.13	-.23	-.29	-.01	.	-.21	-.26	.02	-.01	-.12	-.18
CU	-.62	.54	-.28	-.03	-.18	-.25	-.29	.39	-.18	.01	-.09	-.11	.	-.17	-.21	.19	-.04	-.01	-.06
ZN	.14	.68*	.54	-.09	.61*	-.37	-.40	-.59	.61*	-.45	-.45	.13	.	-.26	-.28	-.31	-.06	-.29	-.32
BR	-.41	.13	-.32	-.27	-.15	-.03	-.12	.10	-.15	.10	.13	.13	.	-.33	-.41	-.29	-.26	-.29	-.25
AG	-.14	.25	.06	.54	.36	-.53	-.58	-.25	.36	-.29	-.38	.49	.	.11	.16	.39	.55	.37	.28
CD	.07	.63	.44	-.15	.17	-.32	-.21	-.15	.17	-.05	-.20	.01	.	-.38	-.30	-.22	-.13	-.17	-.25
SN	-.01	.22	.13	-.06	.27	-.33	-.29	-.22	.27	-.12	-.10	-.07	.	-.24	-.20	-.18	-.04	-.11	-.11
PB	-.63	.59	-.26	.13	.12	-.38	-.49	.12	.12	-.27	-.39	.08	.	-.09	-.17	.17	.13	-.01	-.12
OC	1.00	.23	.98**	.12	.39	.11	-.27	-.56	.39	.06	.38	-.03	.	.16	.00	-.11	.14	.19	.29
EC	.23	1.00	.43	-.02	.53	-.32	-.50	-.40	.53	-.41	-.38	-.15	.	-.20	-.34	-.14	.01	-.22	-.21
TC	.98**	.43	1.00	.11	.47	.03	-.36	-.60*	.47	-.04	.28	-.06	.	.10	-.07	-.13	.13	.13	.22

2-tailed Signif: * - .01 ** - .001

F.8.3 Broadcast Burns -- Fire Average (p.3 of 4)

	NA	AL	SI	P	S	CL	K	CA	TI	V	CR	MN	FE	NI	CU	ZN	BR	AG	CD	SN	PB	OC	EC	TC
OC	-.71	-.38	-.29	0	.16	-.08	.05	-.15	-.77*	-.47	-.61	-.10	-.18	-.66*	-.62	.14	-.41	-.14	.07	-.01	-.63	1.00	.23	.98**
EC	.14	-.11	-.15	.63	-.31	-.20	.45	.30	.42	.35	.33	.51	-.05	.64	.54	.68*	.13	.25	.63	.22	.59	.23	1.00	.43
TC	-.95	-.38	-.30	.39	.08	-.11	.14	-.08	-.49	-.24	-.40	.01	-.18	-.26	-.28	.54	-.32	.06	.44	.13	-.26	.98**	.43	1.00
CARBON	-.92	-.19	-.22	-.17	.11	-.22	-.17	-.07	.13	.32	.20	-.01	-.21	-.01	-.03	-.09	-.27	.54	-.15	-.06	.13	.12	-.02	.11
CMBSTEFF	-.46	.05	.10	.07	.32	.15	.37	.18	-.20	-.13	-.31	-.10	.01	.13	-.18	.61*	-.15	.36	.17	.27	.12	.39	.53	.47
EFPM	.63	-.25	-.20	-.36	-.08	-.02	-.17	-.35	-.28	-.18	-.30	-.45	-.28	-.35	-.25	-.37	-.03	-.53	-.32	-.33	-.38	.11	-.32	.03
EFPM2.5	.52	-.07	-.05	-.34	-.25	-.08	-.20	-.17	-.21	-.24	-.22	-.24	.01	-.42	-.29	-.40	-.12	-.58	-.21	-.29	-.49	-.27	-.50	-.36
EFCO	.40	-.05	-.13	-.02	-.36	-.28	-.44	-.11	.53	.37	.64*	.29	.04	.05	.39	-.59	.10	-.25	-.15	-.22	.12	-.56	-.40	-.60*
EFCO2	-.46	.05	.10	.07	.32	.15	.37	.18	-.20	-.13	-.31	-.10	.01	.13	-.18	.61*	-.15	.36	.17	.27	.12	.39	.53	.47
EFCH4	.76	-.13	-.08	-.03	-.04	.01	-.19	-.13	.10	-.01	.11	-.08	-.09	-.23	.01	-.45	.10	-.29	-.05	-.12	-.27	.06	-.41	-.04
EFNMHC	.46	-.08	-.05	-.08	.27	.07	-.16	-.16	-.21	-.05	-.21	-.31	-.12	-.29	-.09	-.45	.13	-.38	-.20	-.10	-.39	.38	-.38	.28
W_FLUX	-.99	-.04	-.08	.12	-.09	.05	.02	-.01	-.18	-.10	.00	.08	-.09	-.01	-.11	.13	.13	.49	.01	-.07	.08	-.03	-.15	-.06
I_R	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
C_PM	-.94	-.34	-.34	-.40	.06	-.22	-.27	-.25	-.04	.18	.05	-.26	-.38	-.21	-.17	-.26	-.33	.11	-.38	-.24	-.09	.16	-.20	.10
C_PM2.5	-.99	-.24	-.27	-.35	-.02	-.26	-.29	-.15	-.05	.06	.10	-.15	-.24	-.26	-.21	-.28	-.41	.16	-.30	-.20	-.17	.00	-.34	-.07
CO_PPM	-.96	-.21	-.27	-.17	-.16	-.32	-.33	-.07	.36	.51	.54	.15	-.20	.02	.19	-.31	-.29	.39	-.22	-.18	.17	-.11	-.14	-.13
CO2_PPM	-.91	-.18	-.21	-.16	.14	-.20	-.15	-.06	.11	.31	.17	-.02	-.21	-.01	-.04	-.06	-.26	.55	-.13	-.04	.13	.14	.01	.13
CH4_PPM	-.95	-.25	-.26	-.16	.09	-.18	-.26	-.12	.14	.29	.27	-.04	-.27	-.12	-.01	-.29	-.29	.37	-.17	-.11	-.01	.19	-.22	.13
NMHC_PPM	-.69	-.21	-.23	-.22	.24	-.14	-.24	-.15	-.01	.31	.06	-.20	-.28	-.18	-.06	-.32	-.25	.28	-.25	-.11	-.12	.29	-.21	.22

2-tailed Signif: * - .01 ** - .001

F.8.4 Broadcast Burns -- Fire Average (p.4 of 4)

	OC	EC	TC	CARBON	CMBSTEFF	EFPM	EFPM2.5	EFCO	EFCO2	EFCH4	EFNMHC	W_FLUX	I_R	C_PM	C_PM2.5	CO_PPM	CO2_PPM	CH4_PPM	NMHC_PPM
OC	1.00	.23	.98**	.12	.39	.11	-.27	-.56	.39	.06	.38	-.03	.	.16	.00	-.11	.14	.19	.29
EC	.23	1.00	.43	-.02	.53	-.32	-.50	-.40	.53	-.41	-.38	-.15	.	-.20	-.34	-.14	.01	-.22	-.21
TC	.98**	.43	1.00	.11	.47	.03	-.36	-.60*	.47	-.04	.28	-.06	.	.10	-.07	-.13	.13	.13	.22
CARBON	.12	-.02	.11	1.00	.65**	-.57*	-.64**	-.40	.65**	-.61*	-.39	.51	.	.69**	.77**	.75**	.00**	.67**	.66**
CMBSTEFF	.39	.53	.47	.65**	1.00	-.52	-.71**	-.90**	1.00**	-.76**	-.50	.10	.	.33	.30	.13	.68**	.18	.25
EFPM	.11	-.32	.03	-.57*	-.52	1.00	.76**	.23	-.52	.35	.29	-.25	.	-.07	-.29	-.45	-.57*	-.44	-.38
EFPM2.5	-.27	-.50	-.36	-.64**	-.71**	.76**	1.00	.54*	-.71**	.45	.17	-.38	.	-.32	-.27	-.42	-.64**	-.50	-.53
EFCO	-.56	-.40	-.60*	-.40	-.90**	.23	.54*	1.00	-.90**	.57*	.26	-.01	.	-.22	-.10	.16	-.43	-.04	-.15
EFCO2	.39	.53	.47	.65**	1.00**	-.52	-.71**	-.90**	1.00	-.76**	-.50	.10	.	.33	.30	.13	.68**	.18	.25
EFCH4	.06	-.41	-.04	-.61*	-.76**	.35	.45	.57*	-.76**	1.00	.73**	-.16	.	-.45	-.46	-.31	-.63*	-.05	-.12
EFNMHC	.38	-.38	.28	-.39	-.50	.29	.17	.26	-.50	.73**	1.00	-.16	.	-.21	-.32	-.22	-.40	.04	.24
W_FLUX	-.03	-.15	-.06	.51	.10	-.25	-.38	-.01	.10	-.16	-.16	1.00	.	.51	.52	.51	.49	.53	.38
I_R	.	.	.	.	.	.	.	.	.	.	.	.	1.00	.	.	.	.	.	.
C_PM	.16	-.20	.10	.69**	.33	-.07	-.32	-.22	.33	-.45	-.21	.51	.	1.00	.90**	.75**	.65**	.75**	.75**
C_PM2.5	.00	-.34	-.07	.77**	.30	-.29	-.27	-.10	.30	-.46	-.32	.52	.	.90**	1.00	.85**	.74**	.78**	.72**
CO_PPM	-.11	-.14	-.13	.75**	.13	-.45	-.42	.16	.13	-.31	-.22	.51	.	.75**	.85**	1.00	.71**	.84**	.76**
CO2_PPM	.14	.01	.13	.00**	.68**	-.57*	-.64**	-.43	.68**	-.63*	-.40	.49	.	.65**	.74**	.71**	1.00	.63*	.63*
CH4_PPM	.19	-.22	.13	.67**	.18	-.44	-.50	-.04	.18	-.05	.04	.53	.	.75**	.78**	.84**	.63*	1.00	.91**
NMHC_PPM	.29	-.21	.22	.66**	.25	-.38	-.53	-.15	.25	-.12	.24	.38	.	.75**	.72**	.76**	.63*	.91**	1.00

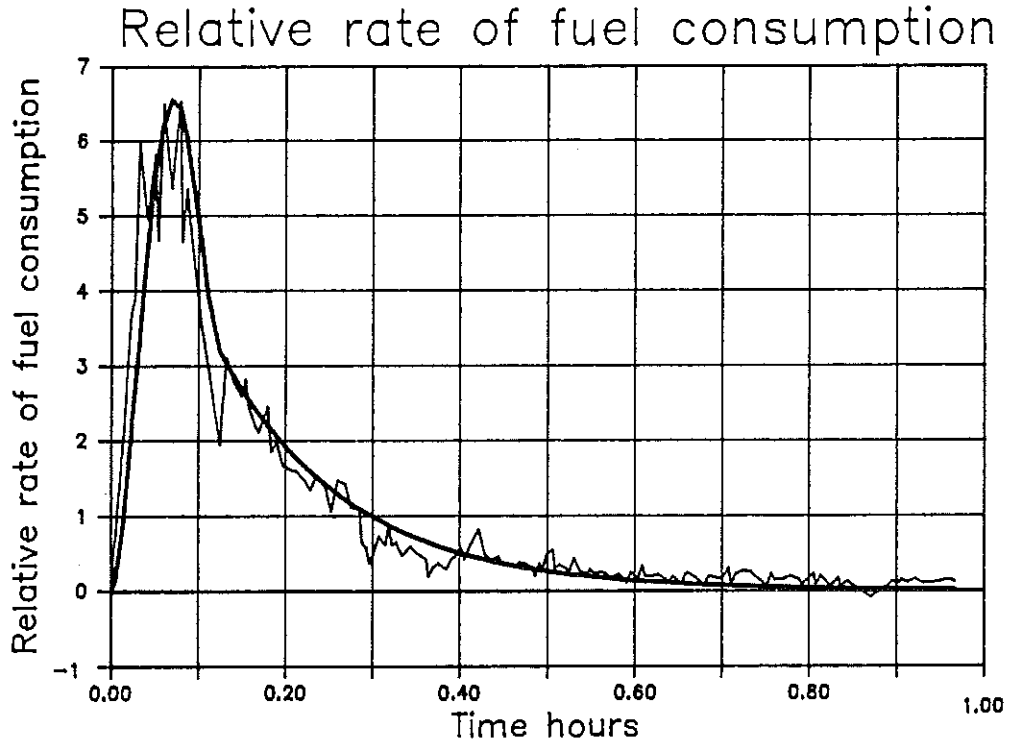
2-tailed Signif: * - .01 ** - .001

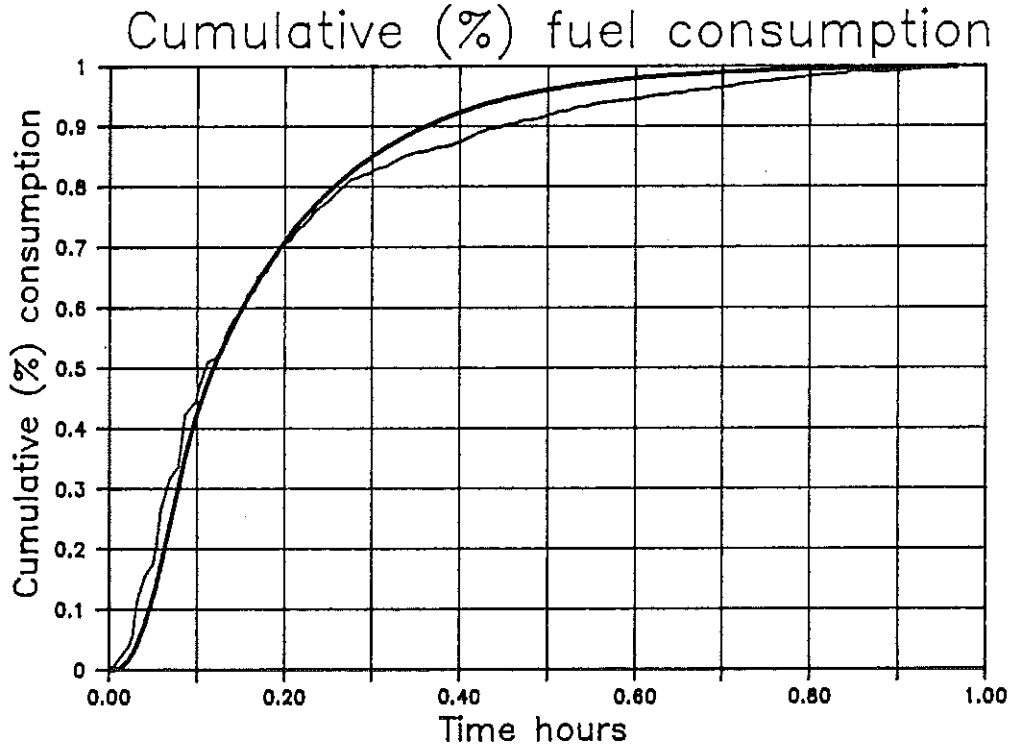
-- APPENDIX G --

Modeled Fuel Consumption Plots

G.1 Modeled fuel consumption profile -- CC1

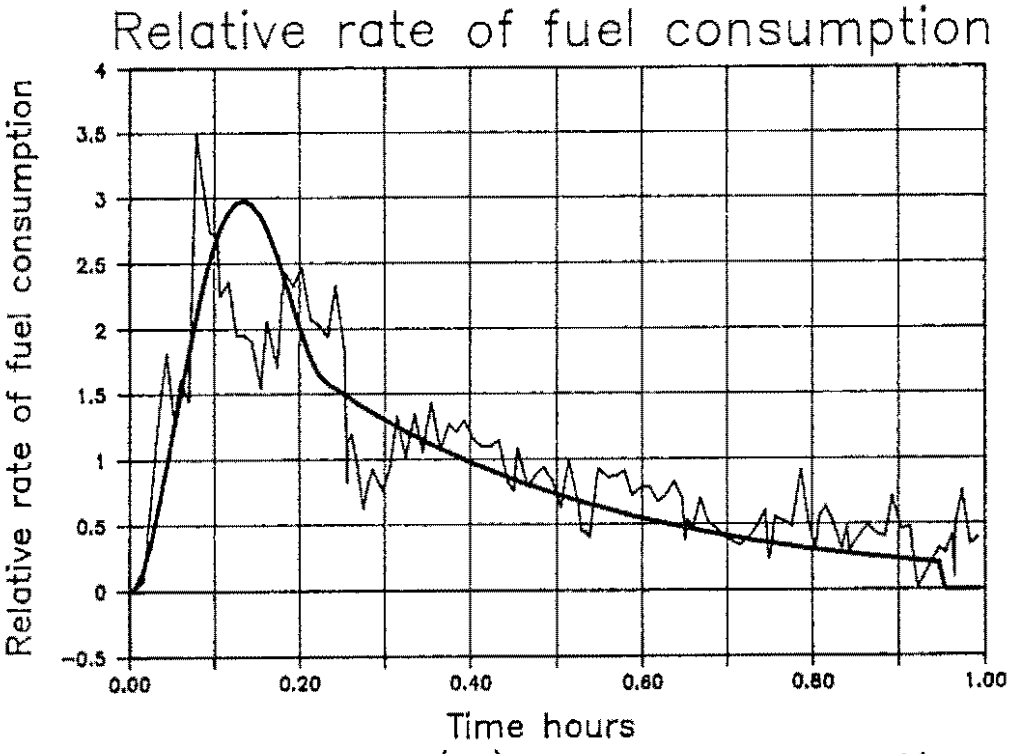
tf=.124 Alpha=.519 Beta=3.2

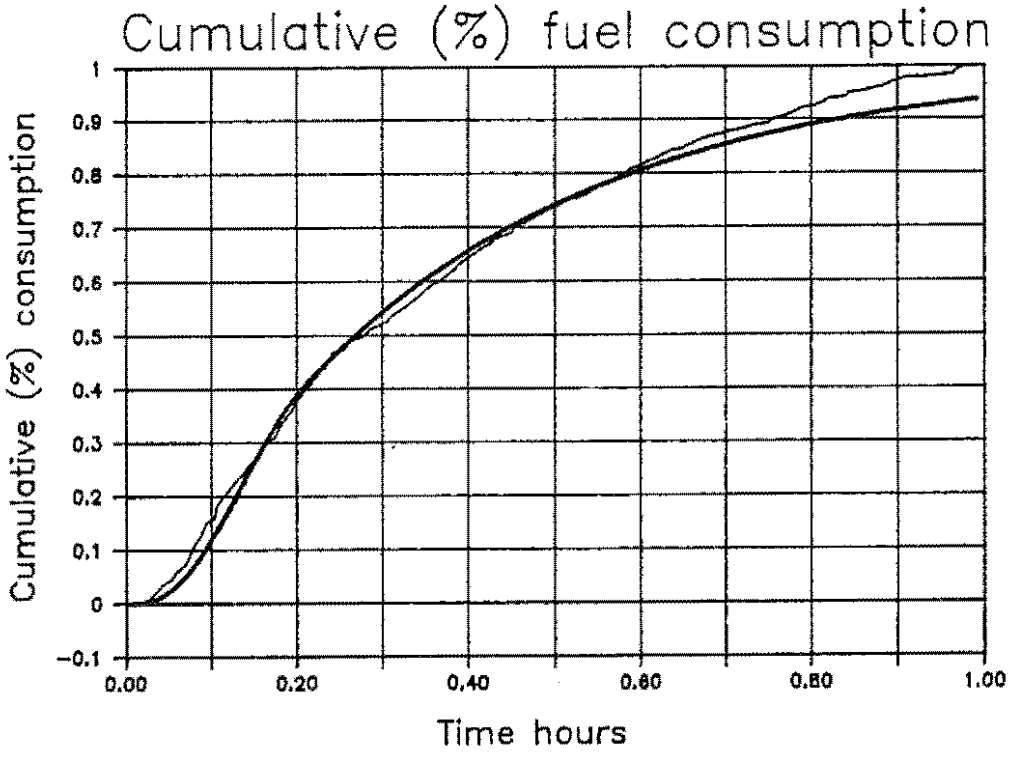




G.2 Modeled fuel consumption profile -- CC2

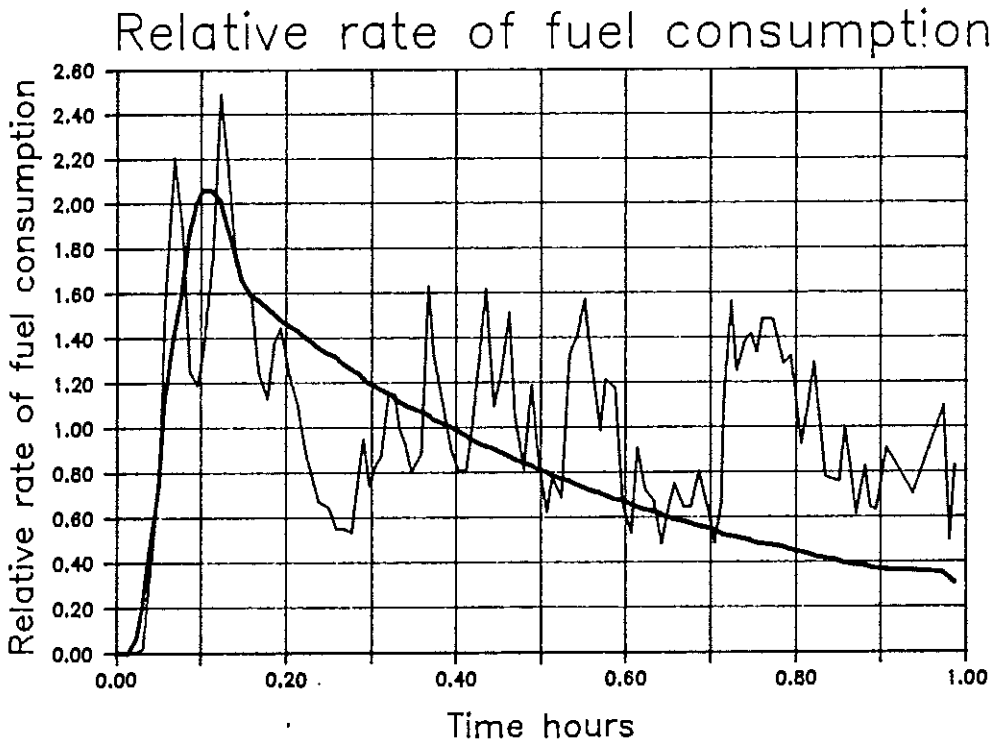
tf=.23 Alpha=.443 Beta=1.6

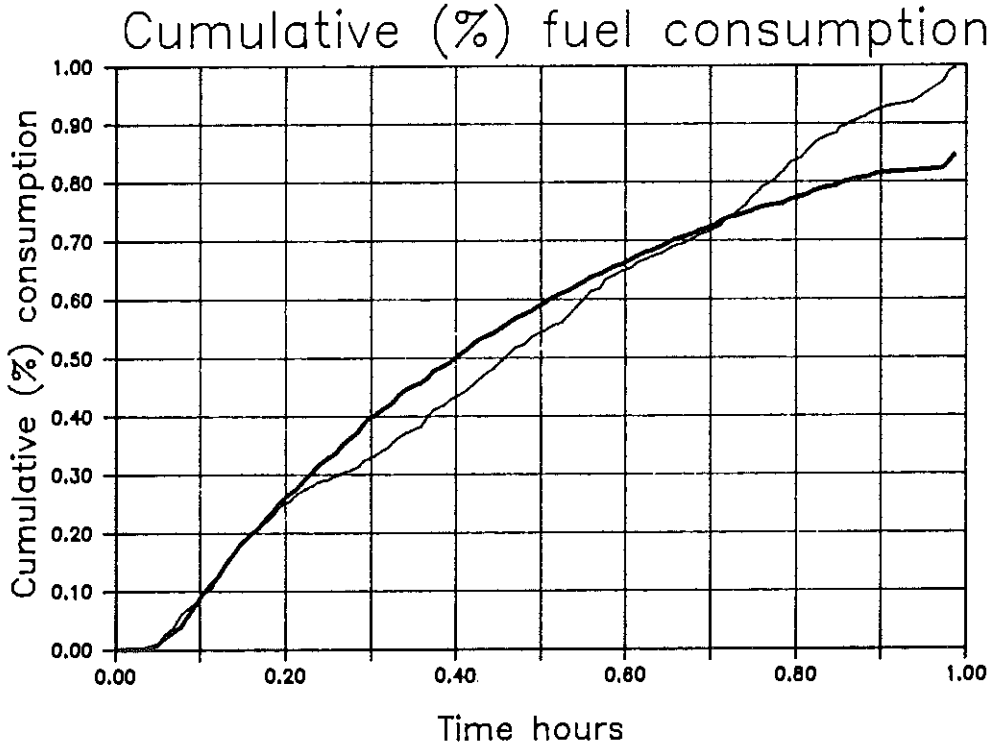




G.3 Modeled fuel consumption profile -- LB1

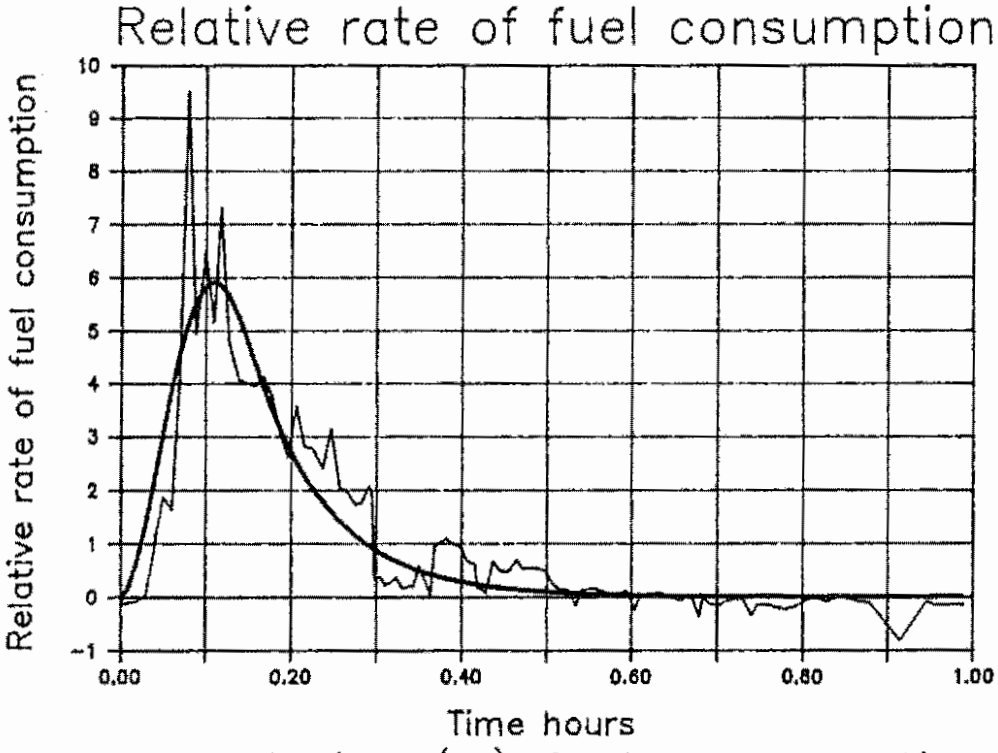
tf=.142 Alpha=.197 Beta=1.59

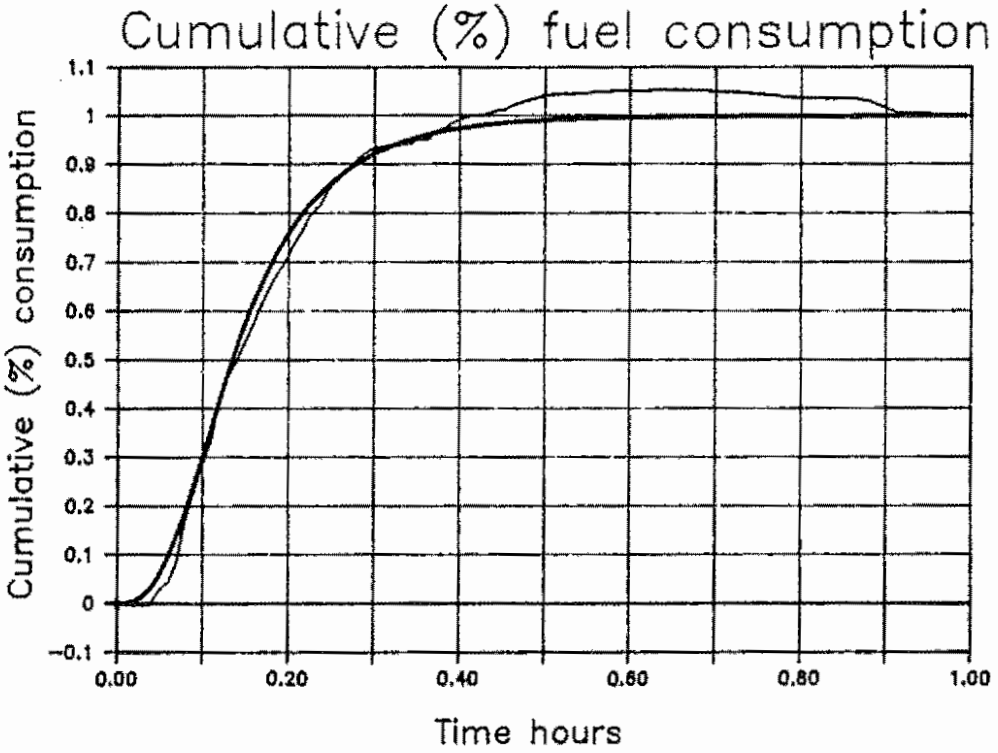




G.4 Modeled fuel consumption profile -- LB2

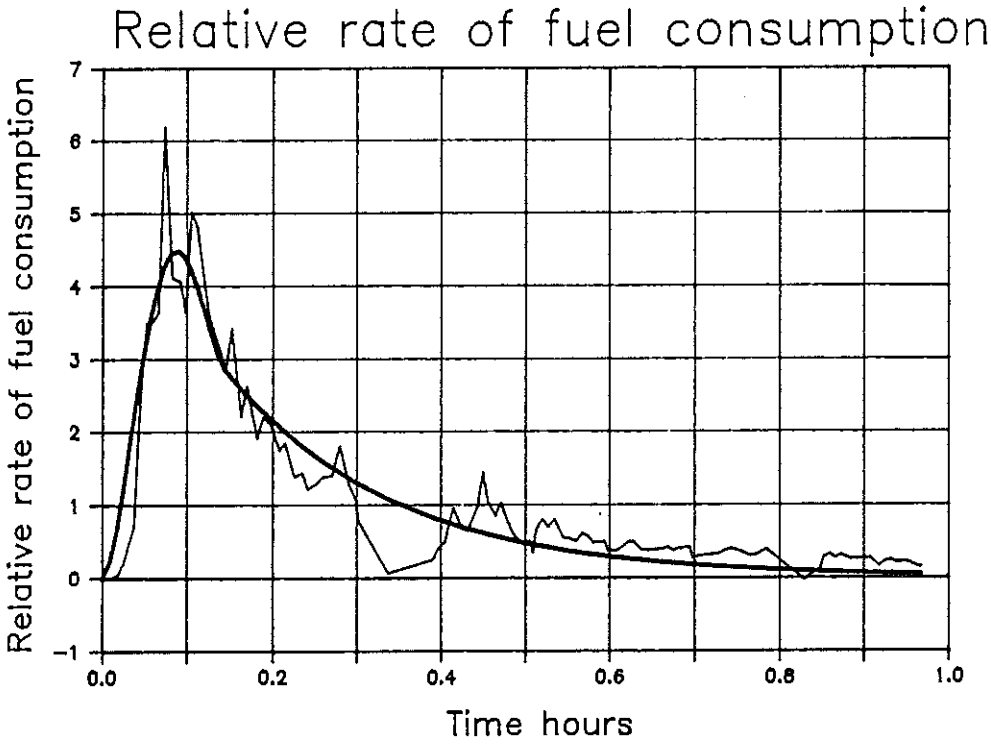
tf=.167 Alpha=.647 Beta=4

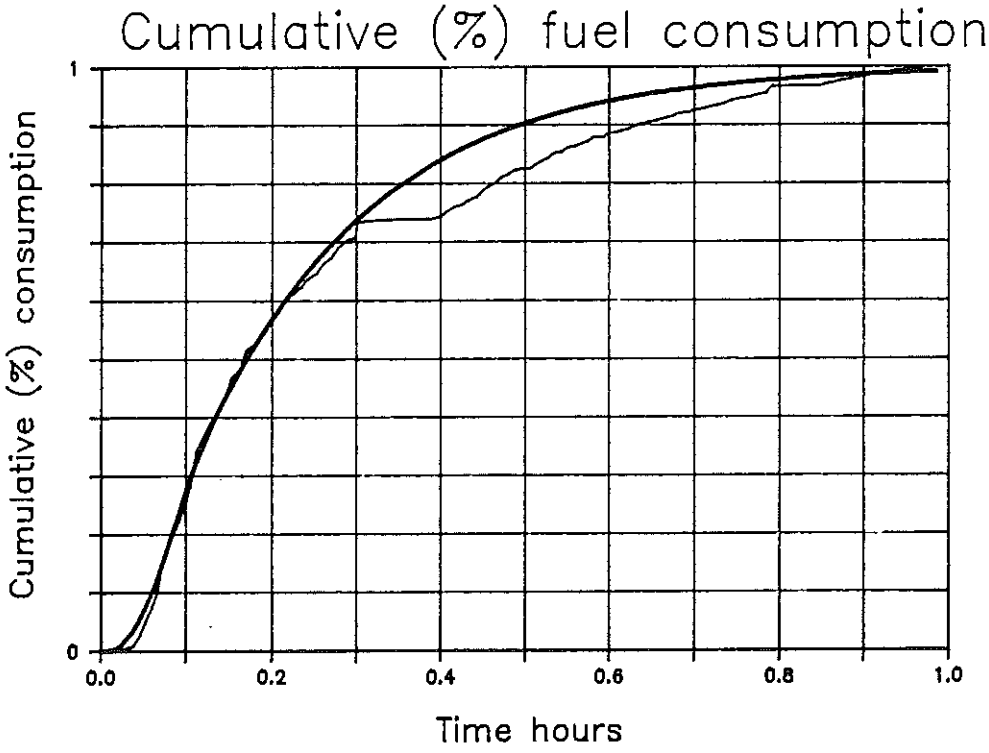




G.5 Modeled fuel consumption profile -- LB3

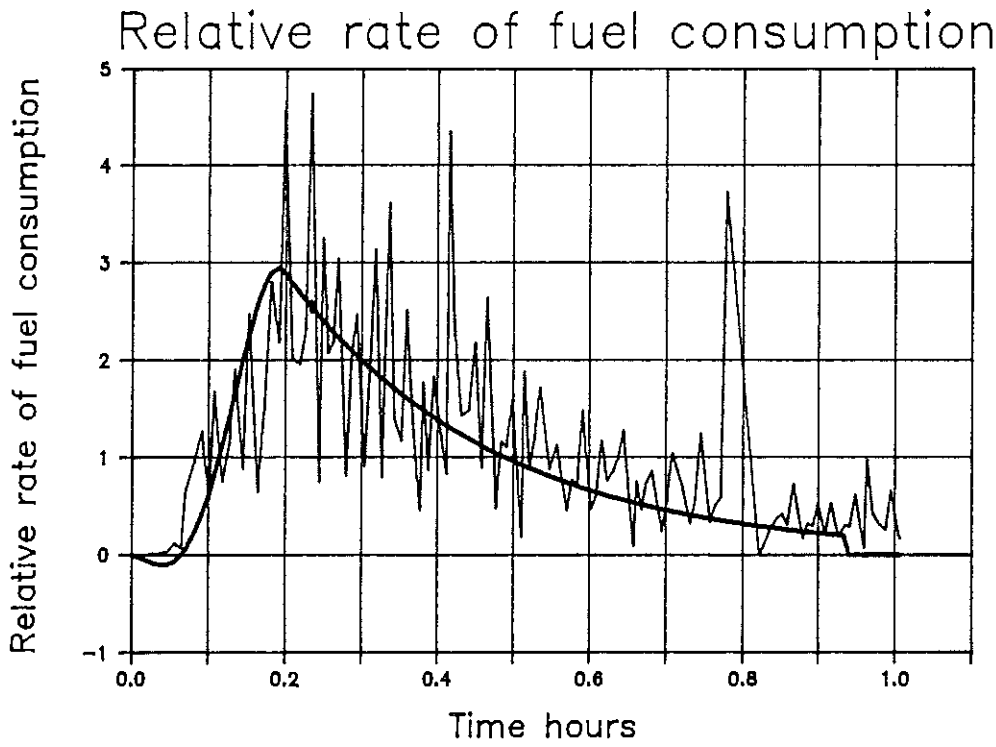
tf=.146 Alpha=.431 Beta=2.85

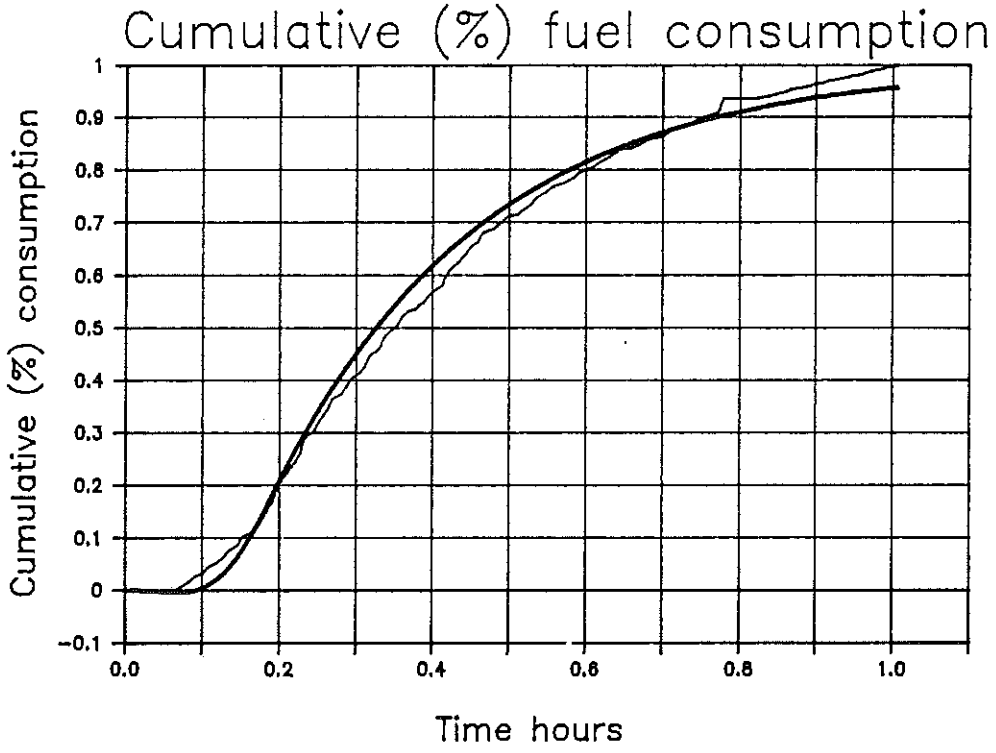




G.6 Modeled fuel consumption profile -- LB4

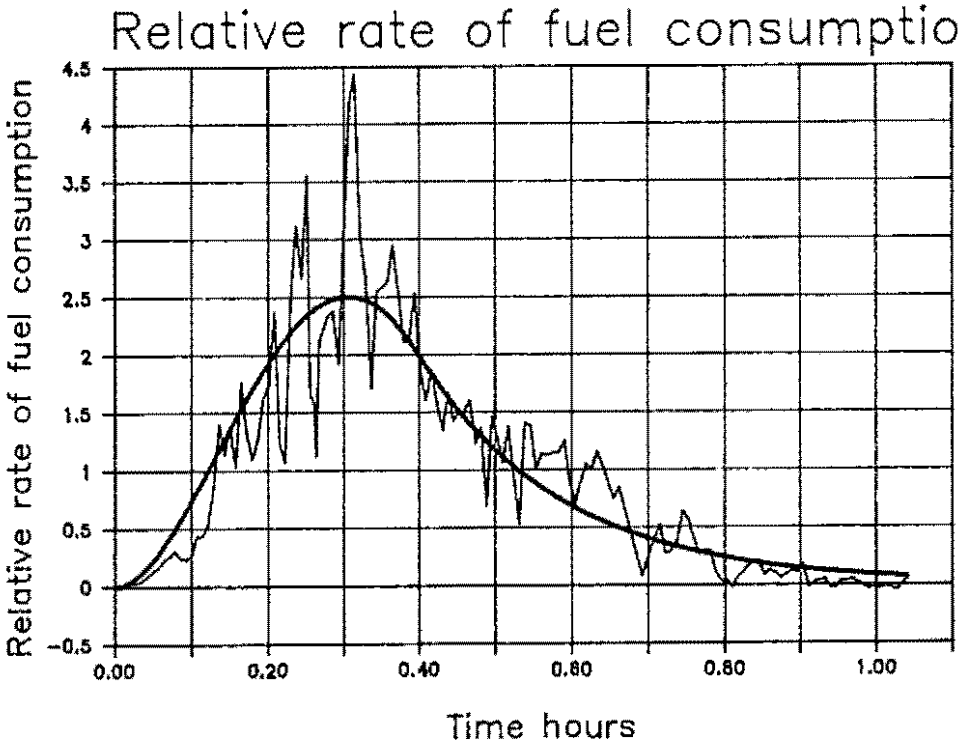
tf=.198 Alpha=.203 Beta=2.92

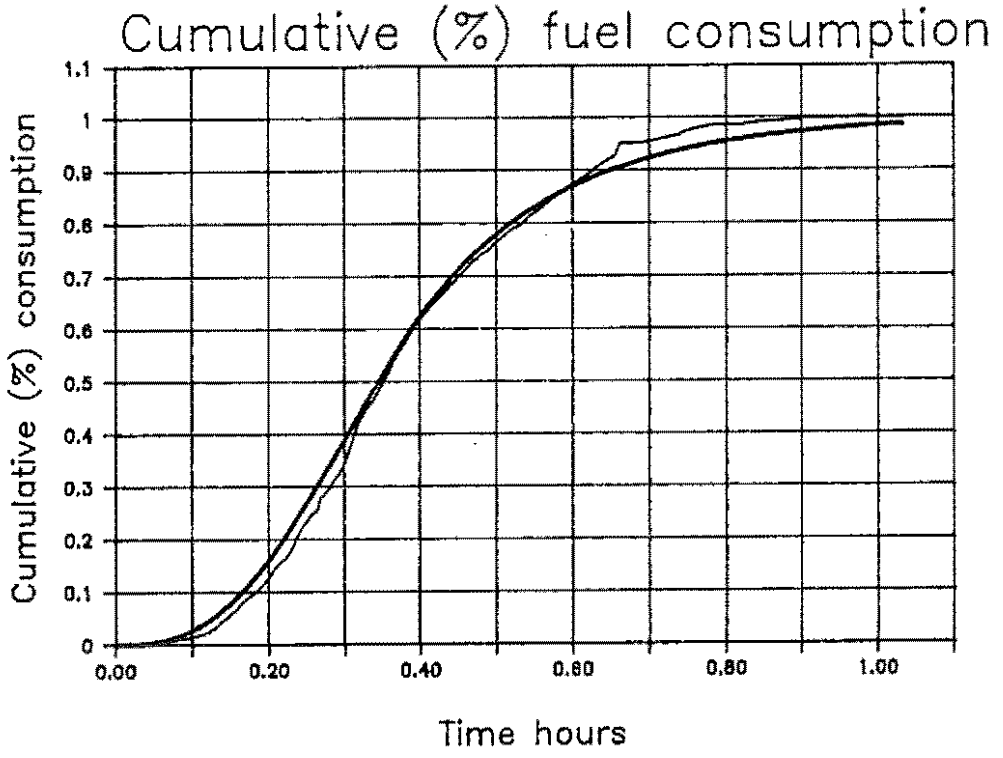




G.7 Modeled fuel consumption profile -- GHA

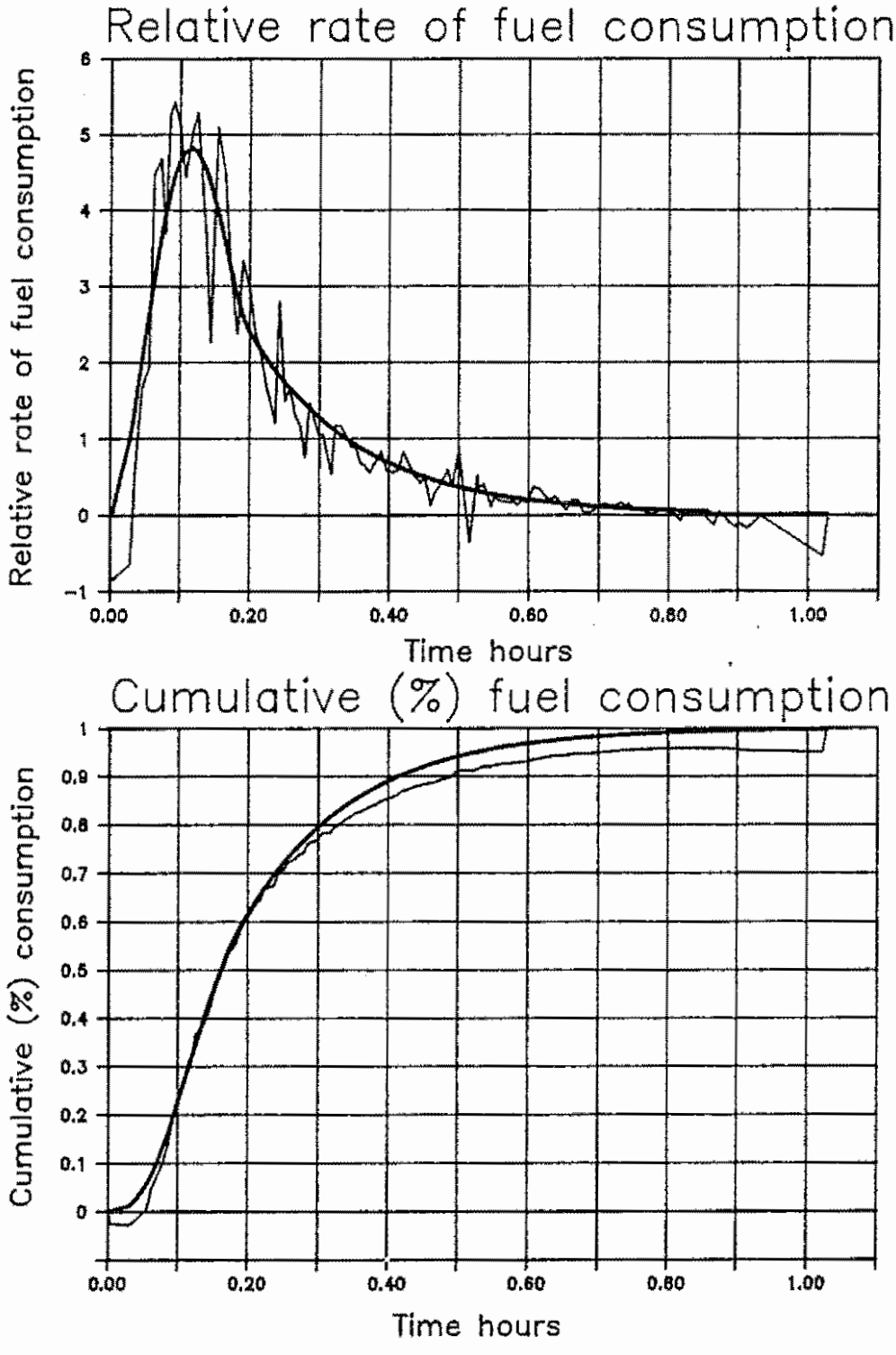
tf=.40 Alpha=.624 Beta=2





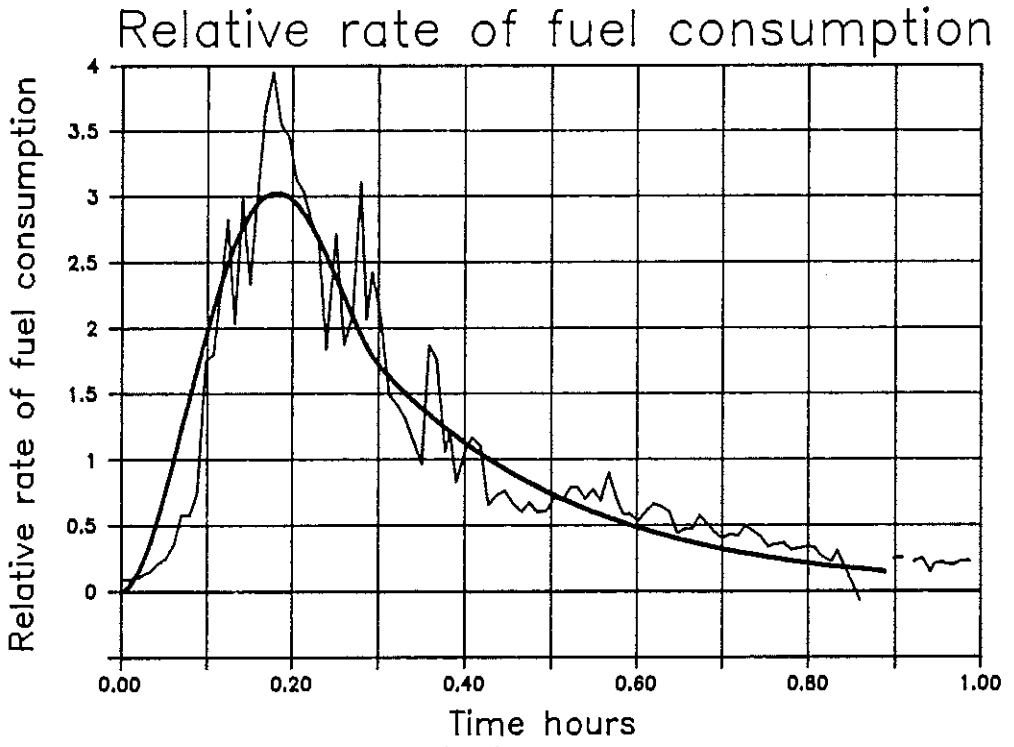
G.8 Modeled fuel consumption profile -- LL2

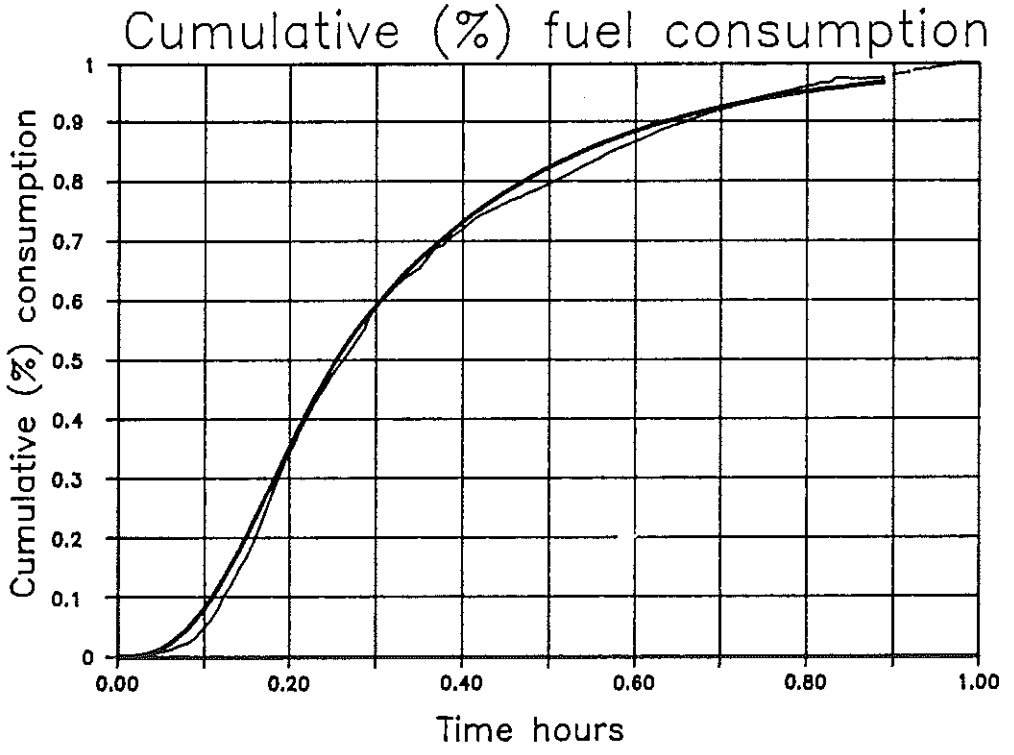
tf=.200 Alpha=.617 Beta=2.4



G.9 Modeled fuel consumption profile -- WHH

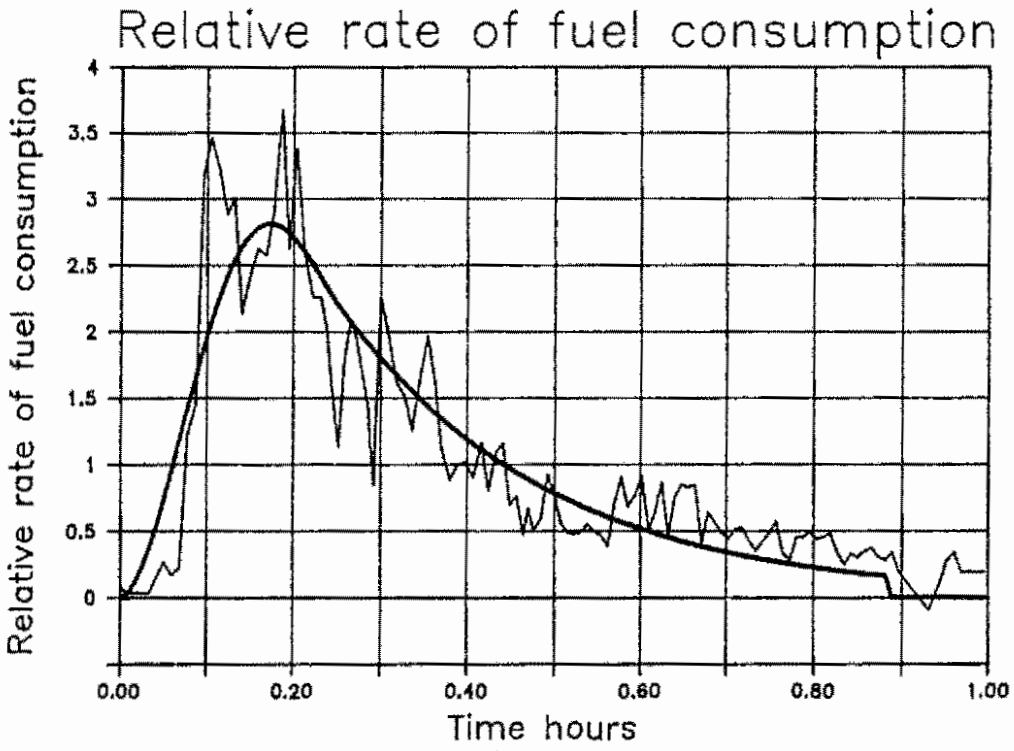
tf=.303 Alpha=.596 Beta=1.7

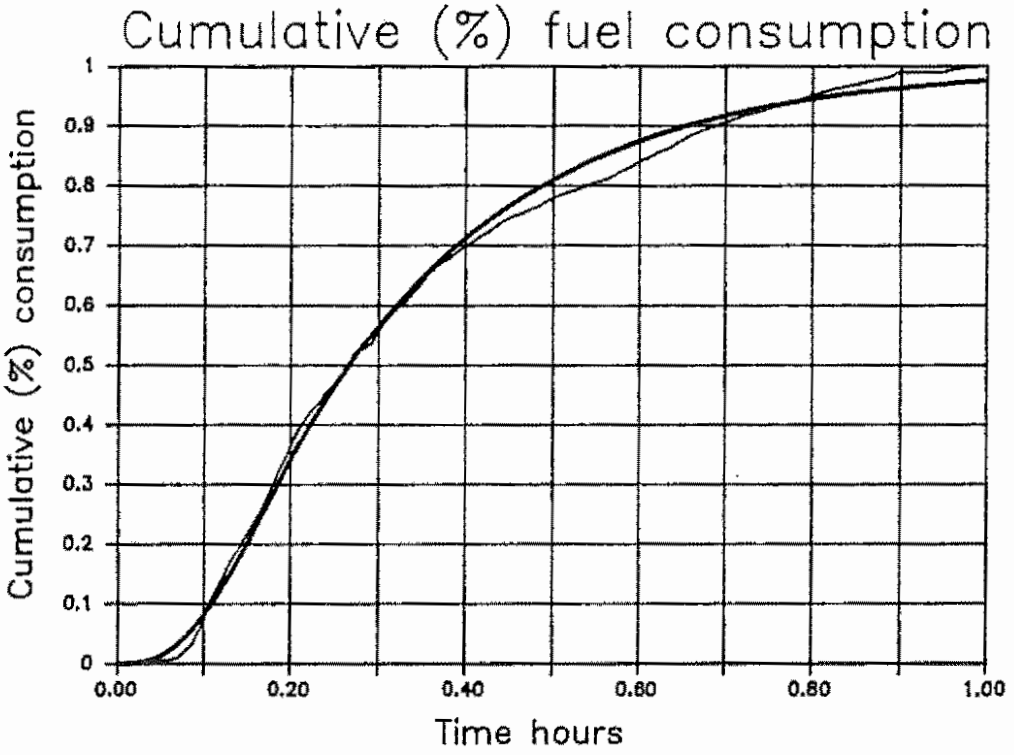




G.10 Modeled fuel consumption profile -- CPC

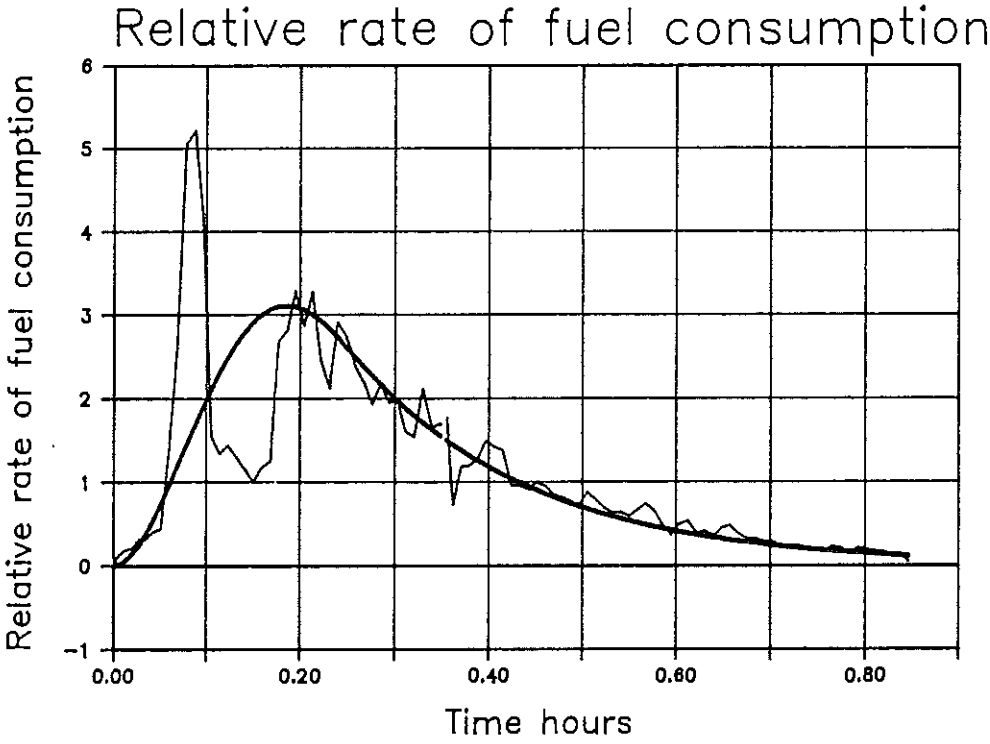
tf=.25 Alpha=.47 Beta=2.2

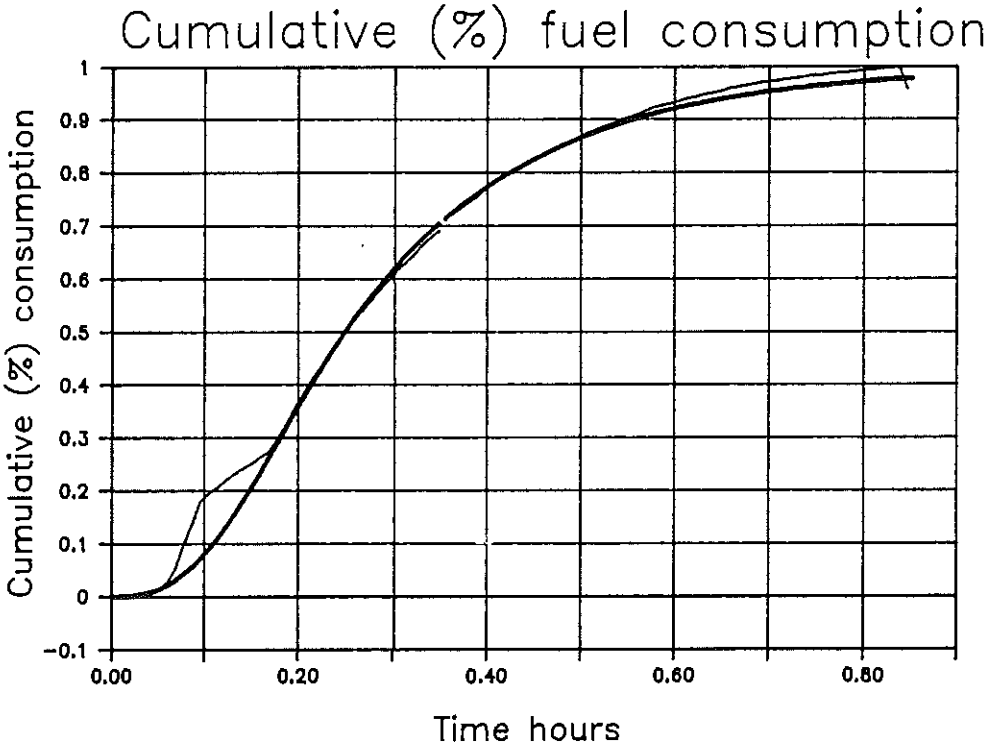




G.11 Modeled fuel consumption profile -- RSP

tf=.258 Alpha=.524 Beta=2.5





G.12 Modeled fuel consumption profile -- VIC

tf=.233 Alpha=.541 Beta=2